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This report summarizes two significant achievements from this research: (1) successful development of a CW mode-locked Nd:glass laser system which is capable of delivering 0.5 ps pulses with 11 μJ/pulse at 400 Hz, 30 fs pulses with 70 nJ/pulse at 400 Hz. This is a world record at this wavelength, (2) natural and synthetic diamond photoconductive devices have been developed for high field (> MV/cm and high-speed (ps) applications.

There are five (5) publications included here as appendices.

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Summary of the Project

The research objectives are:

1. To develop and study modelocked lasers as sources for fast optical signal processing.

2. To assess all aspects of picosecond optoelectronic devices based on transient photoconductivity effect as signal processor.

Within these general and broad objectives, we have undertaken the following areas of research tasks:

1. Develop compact, high-power sources of short pulses.

2. Develop new photoconductive materials capable of high-field applications.

The progress to date is summarized as follows:

1. The argon laser pumped, continuously operating Nd: glass laser, previously modelocked in our laboratory to generate 7 ps pulses at 100 MHz repetition rate, has been further developed to include a Nd: glass regenerative amplifier which not only amplifies the pulse energy by over 10^4 to 11 μJ at a 370 Hz repetition rate but also broaden the pulse spectrum by self-phase-modulation which leads to 0.55 psec pulsewidth after compression. These optical pulses have also been compressed with an optical fiber to 30 fs. A semiconductor laser pumped version of the system is under development.

2. Natural and synthetic diamond photoconductive devices have been developed for high-field ($> MV/cm$) and high-speed ($< 1ns$) applications. Devices developed include photoconductive switches, and photodiodes.

Since most of the results have been or to be published in scientific journals, we will describe each project very briefly. The list of publications for each project is included as part of the project description while the reprints and preprints are enclosed in the appendices which should be regarded as an integral part of this report.

Project Description

1. High Repetition Rate Nd: phosphate Glass Oscillator and Regenerative Amplifier System.

The CW neodymium laser was first modelocked by us to emit 7 ps pulses. We have further developed the system by adding a regenerative amplifier, also made of Nd: glass and pumped by the same argon laser as the modelocked oscillator. The amplifier not only amplifies the pulse energy by more than 10^4 to 20 μJ, it also broadens the pulse spectrum by self-phase modulation to from $2\mathring{A}$ to $15\mathring{A}$. After compression with a pair of gratings, the amplified pulses are 0.55 ps and has an energy of 11 μJ at a 370 Hz repetition rate. Using a regenerative amplifier to broaden pulse spectrum overcomes the major short-coming of the conventional method with optical fibers: optical power limitation. Much higher opical power can be used in the regenerative amplifer than in the fiber core. The details are in Appendices 1 and 2.

These amplified and compressed pulses, after attenuation to avoid optical damage, can be further compressed by an optical fiber. The finally compressed pulses are only 30 fs short, a record for neodymium systems. (The details are in Appendix 3).

The pumping source of our system is argon laser. To make a more compact and more reliable system, we have started developing a diode laser pumped version. We have already succeeded in modelocking the oscillator, with about 30 mw average output at 1 μm using 1 w of pump power. The pulsewidth is 30 ps. The modelocked oscillator is shown in Fig. 1. The diode lasers are combined with a polarizing beam splitter and focussed onto a fiber whose function is to convert the diode laser beams to a smooth, circular beam profile so that it can be better focussed on the Nd: glass gain medium. The laser is modelocked with an acouste-optic modulator.

Publications

1. "An Actively Mode-locked Continuous Wave Nd: Phosphate Glass Laser Oscillator and Regenerative Amplifier," L. Yan, J-D Ling, P.-T. Ho, C. H. Lee and G. L. Burdge, **IEEE J. Quan. Elec.**, 24, pp 418-426 (1988) (Appendix 1)

2. "Generation of High Power, High Repetition Rate, Subpicosecond Pulses by Intracavity Chirped Pulse Regenerative Amplifier," L. Yan, P.-T. Ho and C. H. Lee, and G. L. Burdge, to appear in **Applied Physics Letters** (Appendix 2)

3. "Femtosecond Pulse Generation at 1.05 μm Using Self-Phase Modulation in a Regenerative Amplifier and a Fiber," L. Yan, P.-T. Ho, C. H. Lee and G. L. Burdge, to be presented at CLEO '89 (Appendix 3)

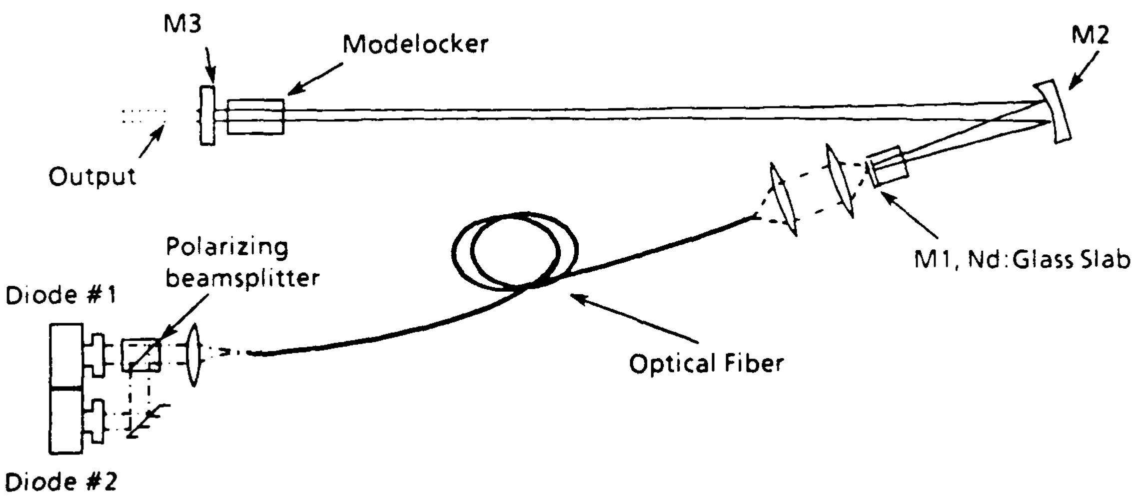

Fig. 1 Diode Laser Pumped Modelocked Nd: Glass Laser

2. Diamond Optoelectronic Devices

Diamond has many attractive properties for high power and high device density applications: (1) high mobility; (2) high dielectric strength; (3) high heat conductivity; (4) high dark resistivity; and (5) hardness to radiation. We have developed optoelectronic devices using both natural and synthetic diamonds. Type IIa, purest of natural diamond crystals, and synthetic films about 1 μm thick grown at low temperature and low pressure by Crystallume, Inc., were used. Both types of diamond were found to be able to hold over 1 MV/cm bias and sensitive to output from N_2 and KrF lasers.

Bulk natural diamonds have been used to study high field effects which are unavoidable in high power and high-density applications. Electrical signals can be switched out with UV laser whose wavelengths be below the diamond bandgap, and up to 10 kV has been switched out (Appendix 4). Nonlinear effects in bias fields have also been observed (Appendix 4). It should be noted that the diamond resistance changes by over 10^{14} with UV light a dynamic range rarely observed in physical experiments.

Synthetic thin films gorwn on p^+ silicon have also been studied. Despite the film's high dark resistivity, the films have observable resistance because the films are only 1 μm thick. Electrical contact was made on the silicon substract, which serves as one electrode, and on top of the diamond film, a thin (100$\AA$) of aluminium was deposited to transmit light, and a thicker aluminium ring was used to complete the second electrode (Fig. 2). Typical current-voltage characteristics are shown in Fig. 3. The device acts electrically as a diode. Incident radiation decreases the device resistance (Fig. 3). Interestingly, the device is responsive to a broad spectrum of light, ranging from 1μm to near UV. Since a diode contact can readily be fabricated, a transistor/photo-transistor on diamond film in our next goal.

Publication

1. "Photoconductive Switching in Diamond under High Bias," J. J. Curry, S. T. Feng, C. H. Lee, P.-T. Ho, and J. Goldhar, Technical Digest, CLEO 1988 pp 110-112 (Appendix 4)

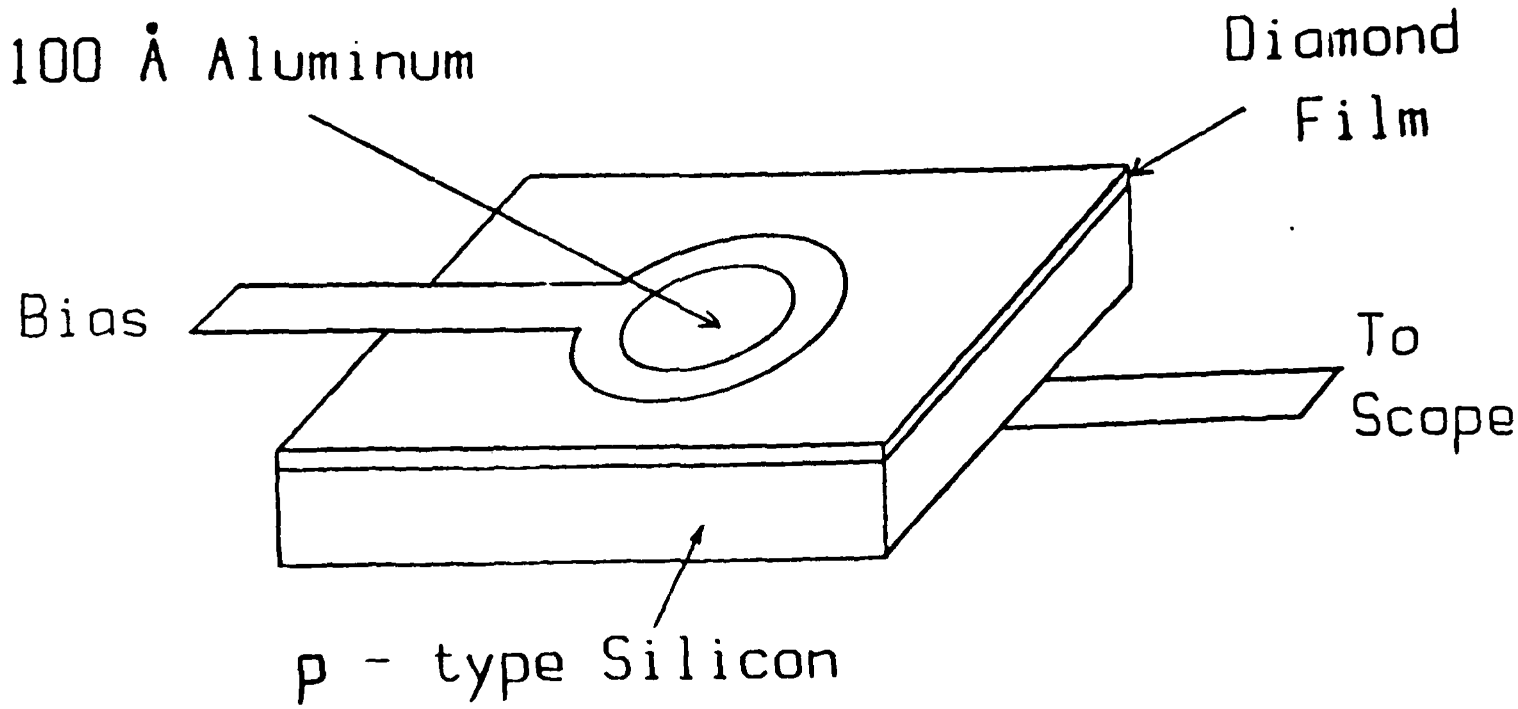

FIGURE 2 Synthetic Film Diamond Switch

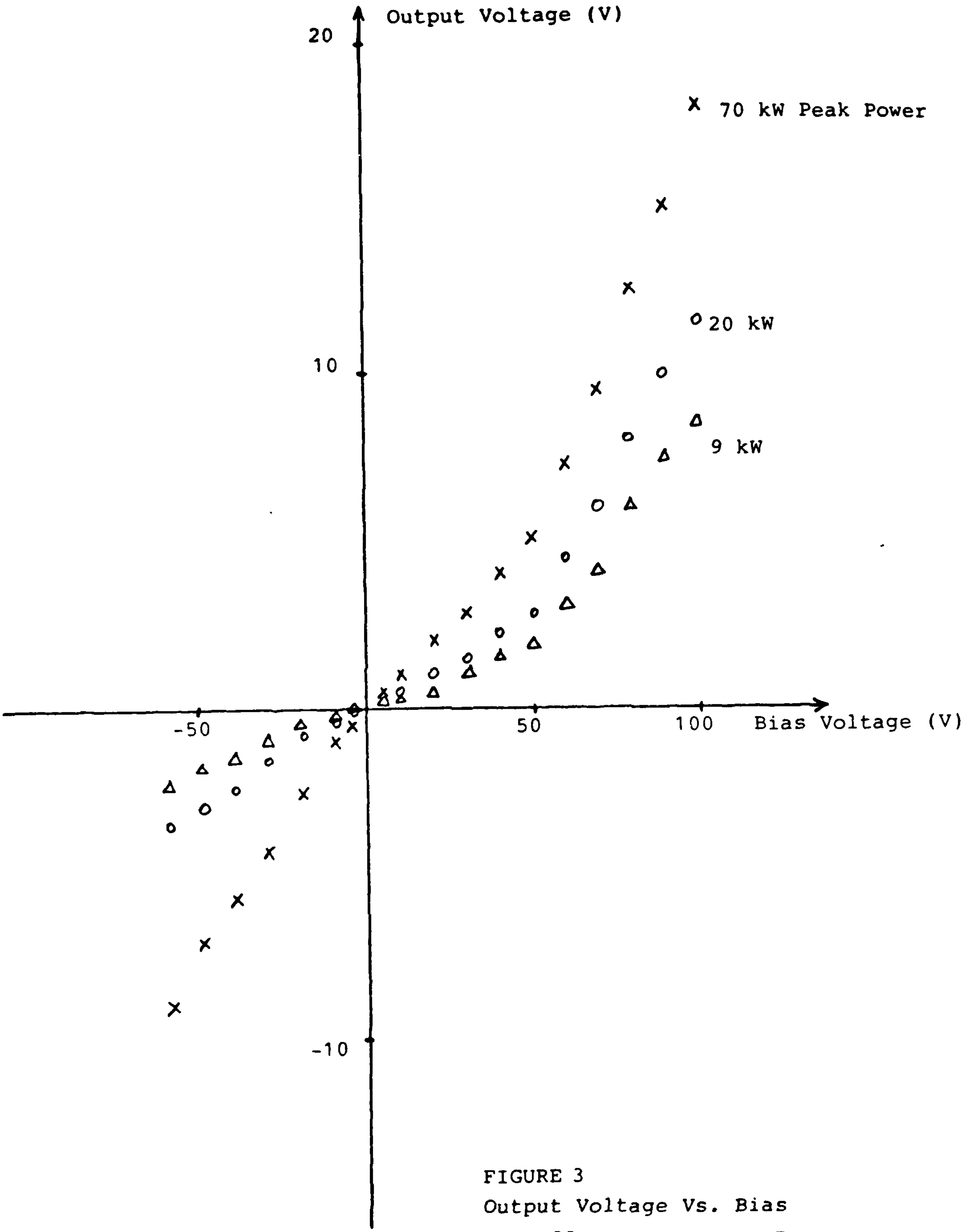

FIGURE 3
Output Voltage Vs. Bias
at Different UV Laser Powers

3. Pulse Evolution in a CW Passively Modelocked Dye Laser

A CPM dye laser was used to study the basic pulse formation mechanism in a passively modelocked laser using a slow saturable absorber. The study concludes that the mechanism proposed by New and Haus is basically correct, and therefore other lasers can be designed on the same principle (Appendix 5).

1. "Evolution of Gain and Absorption in a CW Modelocked Dye Laser," Y. X. Wu and P.-T. Ho, to appear in **Optics Letters** (Appendix 5)

Appendices

1. **"An Actively Mode-locked Continuous Wave Nd: Phosphate Glass Laser Oscillator and Regenerative Amplifier,"** L. Yan, J-D Ling, P.-T. Ho, C. H. Lee and G. L. Burdge, **IEEE J. Quan. Elec.**, 24, pp 418-426 (1988)

2. "Generation of High Power, High Repetition Rate, Subpicosecond Pulses by Intracavity Chirped Pulse Regenerative Amplifier," L. Yan, P.-T. Ho and C. H. Lee and G. L. Burdge, to appear in **Applied Physics Letters**

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5. "Evolution of Gain and Absorption in a CW Modelocked Dye Laser," Y. X. Wu and P.-T. Ho, to appear in **Optics Letters**.

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An Actively Mode-Locked Continuous Wave Nd: Phosphate Glass Laser Oscillator and Regenerative Amplifier

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An Actively Mode-Locked Continuous Wave Nd:Phosphate Glass Laser Oscillator and Regenerative Amplifier

LI YAN, JUN-DA LING, P.-T. HO, CHI H. LEE, AND G. L. BURDGE

Abstract—The performance of a continuous wave actively mode-locked Nd:phosphate glass laser oscillator and a high-repetition-rate Nd:phosphate glass regenerative amplifier is described. Pulses as short as 7 ps at 1.054 μm have been generated at a 100 MHz repetition rate from the laser oscillator. The oscillator output has been amplified by 2×10^5 to 5 μJ/pulse at a repetition rate of 500 Hz.

Introduction

MODE-LOCKED neodymium (Nd) lasers have become indispensable tools for scientific research. Their high-intensity pulses are used to study linear and nonlinear optical phenomena [1], [2]. In all applications, high reliability is required. In many applications, electronically synchronized pulses at a high repetition rate are desired for fast data acquisition.

Although a continuous wave (CW) actively mode-locked Nd:YAG laser can be electronically synchronized and can generate optical pulses at a high rate, it cannot produce short pulses reliably. For instance, because of its narrow fluorescence line width (~ 5 cm^{-1}) [3], [4], the Nd:YAG pulsewidth is limited to about 70–100 ps for modulator driving frequencies of about 50 MHz and moderate modulation depths [5], [7]. Although passively mode-locked Nd:YAG lasers can produce 25 ps pulses [8], [9] and colliding pulse mode-locked lasers can generate 10–12 ps pulses [10], the passive mode-locking process with a saturable dye absorber in these lasers creates a large time jitter, which prevents electronic synchronizing.

The Nd:glass laser, on the other hand, has a broad line width (~ 200 cm^{-1}) and can therefore generate much shorter pulses. Laser pulses of a few picoseconds have been generated from Nd:glass lasers by passive mode-locking [11], [14], active and passive mode-locking [15], or purely active mode-locking [16]. Short pulses from an active mode-locking Nd:glass laser can be synchronized to external equipment. However, these short pulses come with a price. Because of the small stimulated emission cross section (3–4×10^{-20} cm^2), which is an order of magnitude smaller than that of Nd:YAG, a Nd:glass laser has a much higher threshold than a Nd:YAG laser. Furthermore, the thermal conductivity of Nd:glass is also an order of magnitude smaller than that of Nd:YAG. This makes heat dissipation difficult in Nd:glass, and as a result, Nd:glass encounters more severe thermal distortions [12] despite the small thermal-optic coefficient of Nd:glass. In fact, Nd:glass is more easily fractured by thermally induced stress than Nd:YAG. The conventional flash lamp pumping of Nd:glass generates much useless heat at short wavelengths; therefore, short pulses from these Nd:glass lasers are generated by Q-switching at a few hertz repetition rate [11], [16]. Passively mode-locked laser pulses have inherent stochastic fluctuations, so that stability is poor, and synchronizing is impossible.

We have developed a CW actively mode-locked Nd:phosphate glass laser. It combines the advantages of short pulse generation, high repetition rate, and synchronizability. The argon laser longitudinal pump scheme reduces the severe thermal problems, thereby allowing CW operation [17], [18]. The laser has generated pulses as short as 7 ps at 1.054 μm at a 100 MHz repetition rate with >20 mW of average power [19]. In this paper, we will describe the laser construction and performance. This CW actively mode-locked ring laser also provides a unique opportunity to study the pulse formation in an inhomogeneously broadened solid-state laser and to explore some previously unreported properties associated with a ring laser. In the following sections, we will discuss the laser characteristics and compare the characteristics of the mode-locked homogeneously broadened laser and other ring lasers to the Nd:phosphate glass laser.

Recently, many groups [5], [6], [20], [21] have compressed the pulses from a CW actively mode-locked Nd:YAG laser by using an optical fiber and gratings. Pulses have been compressed to the subpicosecond region [5], [21]. However, because of stimulated Raman scattering, the pulse energy after the compression is limited to 1–20 nJ [5], [6], [20], [21]. For higher-intensity applications, the pulse energy has to be amplified further. A Nd:YAG regenerative amplifier can operate at kilohertz repetition rates [22], but its narrow line width prevents it

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from amplifying short pulses. However, a high-repetition-rate Nd : glass amplifier system can produce ultrashort pulses at high repetition rates. We will describe the first operation of such a high-repetition-rate Nd : glass regenerative amplifier, which can amplify the pulse energy up to 5 μJ at a 500 Hz repetition rate.

Laser Oscillator

The ring resonator configuration of the laser oscillator is shown in Fig. 1. The spherical mirror M1 through which the pump beam enters has a dichroic coating for maximum transmission at 514 nm. The laser medium is a rectangular Nd : phosphate glass slab 3 mm thick, 20 mm long, and 15 mm wide [23]. The two 3 × 15 mm surfaces are polished and antireflection (AR) coated at 1.054 μm. The glass slab is wrapped with indium foil and sandwiched between two copper blocks, which are cooled by temperature-controlled running water. The Nd : glass slab is longitudinally pumped by the CW output at 514 nm from an argon ion laser, which is focused at the Nd : glass medium with a beam waist of 65 μm. A standing wave acoustooptic modulator (IntraAction ML-505J) actively mode-locks the Nd : glass laser. Both windows of the modulator are AR coated at 1.06 μm. The modulator is driven with 1.5 W of RF power at about 50 MHz—half of the round-trip frequency of the ring cavity—by a frequency synthesizer with 10 Hz sensitivity and 10^{-9} stability and by a broad-band RF power amplifier. The modulator is cooled by temperature-controlled running water.

CW mode-locking of the Nd : phosphate glass laser was readily achieved with argon-ion pump power greater than 0.8 W and with the intracavity acoustooptic modulator tuned to a cavity resonance around 50 MHz. Although our cavity design provides a large stability range, we have found that it is important to adjust the spacing between the two spherical mirrors to the middle of the stability range. This adjustment results in a cavity which is less sensitive to intracavity elements and more tolerant to the thermal lensing in the glass. Moreover, by operating in the middle of the stable range, the argon-ion pump beam profile has a better match to that of the Nd : glass laser. The argon-ion pump laser power must be held within 0.2 W; otherwise, lasing will cease.

The mode-locked laser performance is monitored by a fast pin-diode detector and sampling oscilloscope. Tuning sensitivity of the acoustooptic modulator driving frequency depends on the pulse duration itself For instance, when pulsewidths are longer than ~ 120 ps, a few hundred hertz shift in driving frquency will not change the pulse duration appreciably. However, when pulsewidths are shorter than ~70 ps, even a 10 Hz shift in driving frequency can appreciably change the pulse duration, as monitored on the sampling oscilloscope. In addition to the acoustooptic modulator tuning effects on the pulsewidth, any etalons created by intracavity elements can also change the pulsewidth, so extensive care has been taken to avoid these effects.

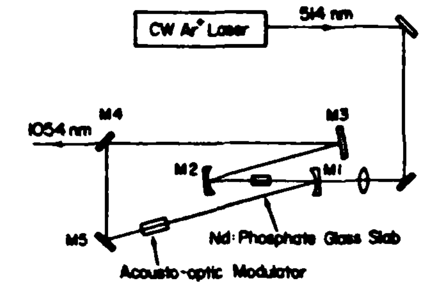

Fig. 1. Schematic of the CW actively mode-locked Nd : phosphate glass laser oscillator. M1 is a dichroic-coated plano-concave mirror with R = 30 cm. M2 is an R = 30 cm plano-concave mirror with HR coating. M3 and M5 are plano mirrors with HR coating. M4 is a plano mirror with a reflectance of 97 percent.

A TEM_{00} transverse mode is essential for the generation of short pulses. With good alignment, a TEM_{00} transverse mode is achieved without any intracavity aperture because the focused pump beam at the medium forms an effective aperture. However, when the resonator is not aligned well, the laser will produce higher-order transverse modes. During operation with higher transverse modes, laser pulses are long (> 150 ps), whereas during TEM_{00} mode operation, laser pulsewidths are reduced appreciably. Such a broad pulsewidth for higher transverse modes is caused primarily by nondegeneracy of the mode spacing for the fundamental and higher-order transverse modes. For a mixture of transverse modes, phase-locking of all the modes becomes difficult.

We have found experimentally that the argon-ion pump level plays an important role in the overall performance of the Nd : glass laser. Basically, as the pump power increases, the laser stability and the pulse coherence improve, and the pulsewidth gets shorter. Fig. 2 summarizes the pulsewidths observed at different pump powers. When the Nd : phosphate glass medium is pumped below 1.1 W, the laser output is not stable, and only ≧ 100 ps pulsewidths can be attained, as observed on the sampling oscilloscope. When the pump power is increased to 1.2 W, pulsewidths shorter than 100 ps are observed. When the pump power is increased to above 1.4 W, pulsewidths less than 50 ps are measured. (These short pulsewidths were measured by the standard collinear intensity autocorrelation method [24].) When the pump power exceeds 1.8 W, good stable laser operation is achieved. The sampling oscillogram of laser pulses (Fig. 3) shows the good stability and reproducibility of the laser, although the pulsewidth is shorter than the detection bandwidth limit of 73 ps. The autocorrelation measurements yield pulsewidths typically between 20 and 30 ps with good coherence characteristics. At a pump power of ~3.2 W, we obtained the shortest pulsewidth of 7 ps (Fig. 4). (To avoid possible damage to the Nd : glass slab, we did not use pump powers higher than 3.3 W.)

The improved performance of the laser as the pump power increases can be explained qualitatively as follows. Although the Nd : phosphate glass is nominally inhomogeneously broadened with an effective fluorescence line

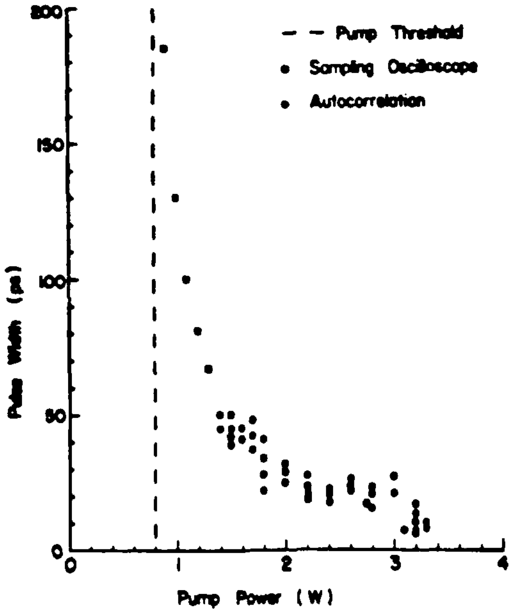

Fig. 2. Pulsewidths observed at different pump powers. The solid squares are measured by a sampling oscilloscope; the circles are measured by autocorrelation.

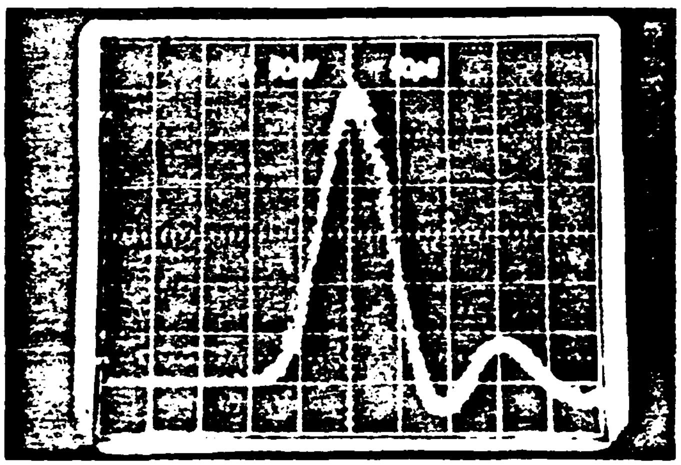

Fig. 3. Sampling oscillogram of the CW mode-locked pulses. The combined response time of the detector and the sampling oscilloscope is 73 ps (FWHM).

width $\Delta f = 6 \times 10^{12}$ Hz, the homogeneous width of each constituent ion species is about 6×10^{11} Hz [25]. This homogeneous width is broad enough to cover many longitudinal modes of the resonator (mode spacing = 100 MHz). The laser is neither strictly homogeneously broadened nor strictly inhomogeneously broadened, but rather it is more homogeneously broadened at low pumping levels and increasingly inhomogeneously broadened at higher pumping levels. Mode-locking a homogeneously broadened laser is more difficult, as the bandwidth comes from side-band generation. Mode-locking an inhomogeneously broadened laser is easier since the bandwidth is already there. Only a small injection signal from side-band generation is required to lock in phase the different components within the free-running bandwidth.

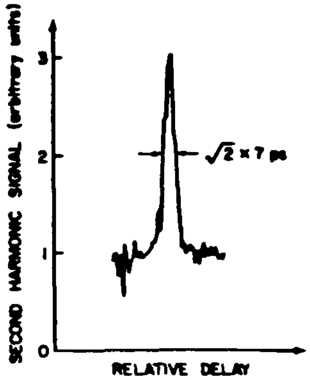

Fig. 4. Autocorrelation trace of pulses from the CW mode-locked Nd:phosphate glass laser. A Gaussian pulse shape is assumed. The 3:1 ratio indicates that pulses are coherent.

Thus, in our case, at lower pumping levels we can estimate the pulsewidth τ_p using theories for actively mode-locked homogeneous lasers [26]. As the pumping level increases, the laser becomes more inhomogeneously broadened, and the free-running bandwidth increases. We can expect the pulsewidth to decrease as the longitudinal modes within the increased bandwidth are locked together, which is indeed what we observe experimentally.

The steady-state pulsewidth τ_p expected from active mode-locking a homogeneously broadened laser is [26], [27]

$$\tau_p = \frac{(2 \ln 2)^{1/2}}{\Pi} \left(\frac{g}{\theta_m^2}\right)^{1/4} \left(\frac{1}{f_m \Delta f}\right)^{1/2} \tag{1}$$

for the single-pass amplitude transmission given by

$$m(t) = \cos(\theta_m \sin 2\Pi f_m t) \tag{2}$$

where Δf is the gain line width, f_m is the modulator driving frequency, θ_m is the modulation depth, and $g \simeq \frac{1}{2} \ln (1/R_{eff})$ is the saturated round-trip amplitude gain. R_{eff} is the effective power reflectivity including all cavity losses.

In our experiment, the following parameters are used or estimated: the Nd:phosphate glass effective fluorescence line width $\Delta f \simeq 6 \times 10^{12}$ Hz, $f_m = 50$ MHz, $\theta_m \simeq 0.4$, and $g \simeq 0.064$. With these parameters, the pulsewidth expected from (1) is $\tau_p \simeq 17$ ps. This value is comparable to the 20–25 ps pulsewidths observed experimentally at some moderate pumping levels. We do observe quite a large pulsewidth variation at lower pumping levels (see Fig. 2). However, in this unstable region of operation, the Kuizenga–Siegman theory [26] can no longer be applied.

At our highest pump power, the shortest pulse generated (only 7 ps) was about twice as short as that predicted by (1). The simultaneous measurement of the pulse spectrum by a spectrometer with a scanning diode array [28] yields a 5.5 Å pulse bandwidth (Fig. 5). We think that such short-pulse generation reflects the following two facts: 1) the increasing importance of inhomogeneous broadening and 2) the involvement of phase modulation.

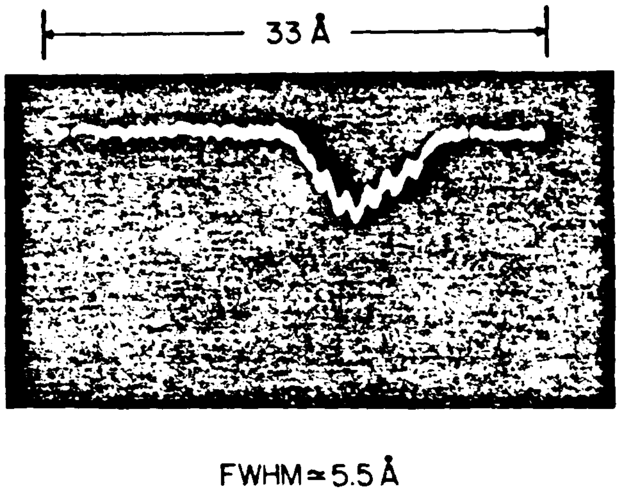

Fig. 5. Spectrum of pulses of 7 ps pulsewidth. FWHM = 5.5 Å. The spectrometer has a resolution of 0.156 Å/diode at 1 μm.

We note that the bandwidth of the 7 ps pulses (5.5 Å) now approaches the homogeneous line width. As the Nd : glass behaves more like an inhomogeneous broadened gain medium, the free-running bandwidth increases, and mode-locking is facilitated. Although coherent, the shortest pulses we obtained (7 ps) did have a bandwidth broader than the minimum required by Fourier transform. (The measured product of pulsewidth-bandwidth is ~1.1.) A modulated structure can clearly be seen in the pulse spectrum (Fig. 5); this structure indicates that such short pulses are indeed phase modulated. Phase modulation broadens the pulse spectral bandwidth, and under proper conditions, it can generate very short pulses.

Self-phase modulation (SPM) occurs commonly in high-power Nd : glass lasers [12], [16], [29]. In a recent experiment, Tomie [16] generated 4 ps pulses at the second harmonic from an actively mode-locked and Q-switched Nd : phosphate glass laser. The mechanism for generating such short pulses is found to be the SPM and interference through a thin etalon [16]. The intracavity laser intensity in that experiment was 300 MW/cm^2, which is above the SPM onset intensity of 150 MW/cm^2 [11]. In our experiment, however, the focused intracavity laser intensity at the Nd : glass medium is about 30 MW/cm^2 (15 nJ intracavity pulse energy and beam waist of 58 μm) even for a pulse duration of 10 ps. The laser intensity at the acoustooptic modulator is two orders of magnitude lower than that at the laser gain medium. Furthermore, no thin etalon is inserted inside our laser cavity. The shortest intracavity element is the 2 cm long Nd : phosphate glass slab; hence, when the pulse duration is less than 100 ps, any possible interference caused by the slab is expected to be very weak. Therefore, the SPM effect, at least, is not the main pulse-shaping mechanism. Instead, we observe a correlation between the onset of the modulated pulse spectrum and a tuning of the modulator driving frequency. At a certain modulator driving frequency, the laser generates pulses (~20 ps), which yield a smooth bell-shaped pulse spectrum with a 2.7 Å bandwidth. When the modulator driving frequency is tuned about 1 kHz above the cavity resonance frequency, the pulse spectrum broadens, and the modulated structure appears. This suggests that some phase modulation is introduced through the detuning in the modulation process and that this phase modulation is involved in the pulse shaping. In fact, for the case of mode-locking by FM [26] when the pulse repetition frequency (twice the modulator driving frequency) is detuned above the cavity resonance frequency, the laser pulsewidth is actually shortened. The short-pulse generation mechanism in our experiment is not yet fully understood, and work on this effect is continuing.

Also, we have observed a directional asymmetry of laser oscillation in our actively mode-locked ring laser oscillator. With the acoustooptic modulator driving power off, CW laser oscillation occurs in both counterpropagating directions with nearly equal intensity. However, with the modulator driving power on and with the Nd : glass laser aligned to give short pulses, the oscillation intensity in one direction is much greater ($\geq$20 times) than that in the other direction. The laser power dropoff in one direction is usually accompanied by an increase in power in the counterpropagating beam. By adjusting the acoustooptic modulator elevation angle (around the Bragg angle), we can flip the dominant laser oscillation from one direction to the other direction. Mandel and Abraham [30] and Lett *et al.* [31] have studied the stability of a bidirectional homogeneously broadened ring laser. For a single-longitudinal-mode oscillation in two directional modes, they found that the symmetric solution is always unstable above threshold, whereas the asymmetric solution has a finite domain of stability. Destabilization of this asymmetric solution causes spontaneous and random switching between the zero-intensity mode and the oscillating mode. However, for multimode lasers, especially mode-locked ring lasers, no theoretical or experimental results of such directional asymmetry of oscillation have been reported. In fact, colliding pulse mode-locking of a ring laser [32] requires two equally intense beams in the two counterpropagating directions. Tomov *et al.* [33] reported a unidirectional traveling wave operation of their mode-locked Nd : glass ring laser. But in their setup, a saturable absorber cell was placed near one end of the laser medium to generate directional discrimination, and the unidirectional oscillation is unique. In our experiment, no discriminative element is deliberately inserted inside the ring cavity, and the modulator is placed a quarter of the cavity length away from the laser medium. Since the fluorescence lifetime of the Nd : glass ($\geq$300 μs) is much longer than the cavity round-trip time (10 ns), cross-saturation effects should be negligible. The mechanism of this previously unreported asymmetric directional oscillation in an actively mode-locked Nd : glass ring laser is not well understood. However, we can again correlate the assymmetric oscillation to the pulse narrowing via the gain level increase since the gain in one direction will be enhanced if an asymmetric oscillation favors that direction.

We have also studied the Nd : glass laser behavior when

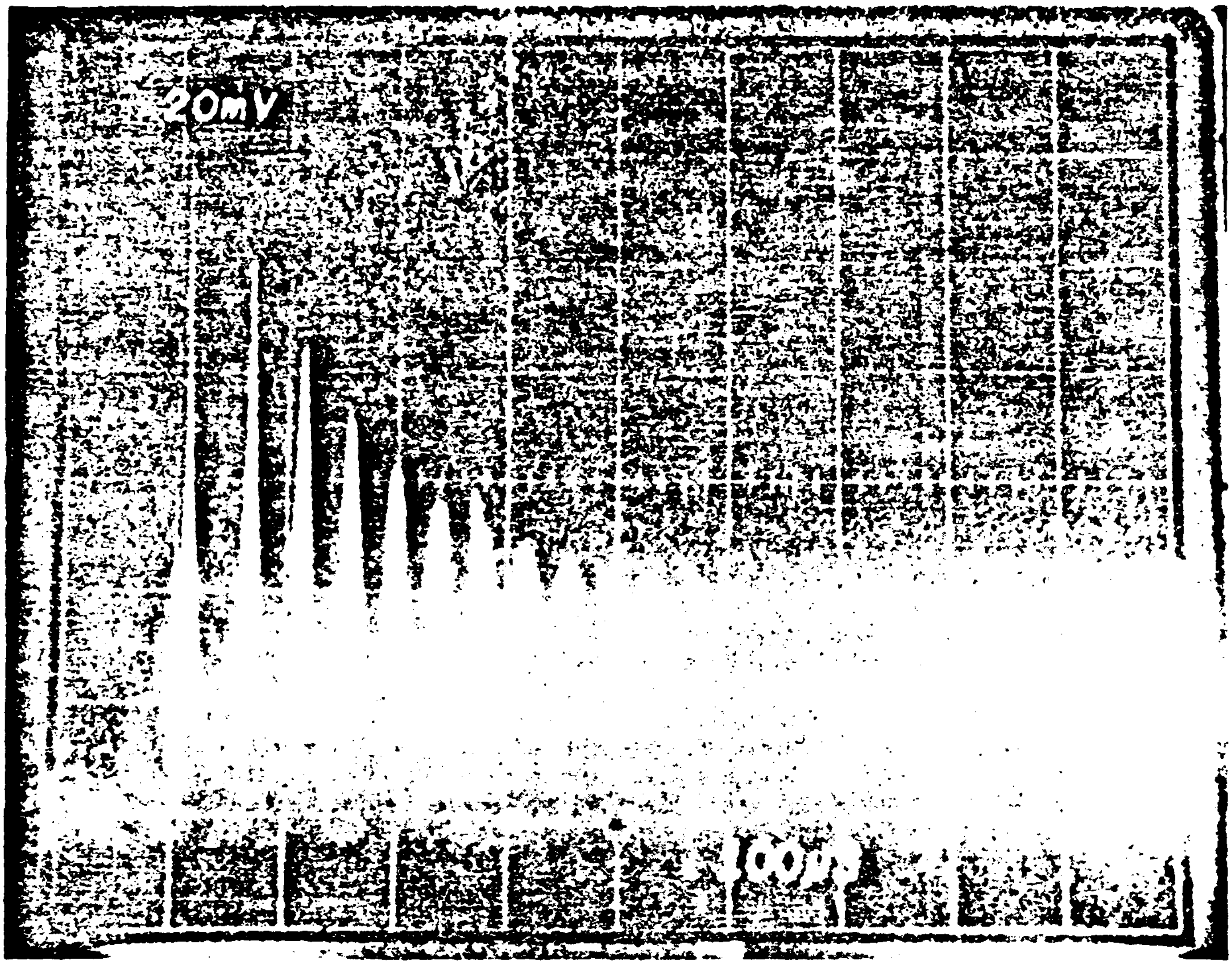

Fig. 6. Simultaneous mode-locking and relaxation oscillations when the pump beam outside the cavity is chopped. Although the individual mode-locked pulses cannot be resolved, the envelope relaxation oscillations can be seen clearly.

a mechanical chopper is used to chop (at a rate between 200 and 500 Hz) either the IR laser beam inside the cavity or the argon-ion laser pump beam outside the cavity. In both cases, simultaneous mode-locking of individual pulses and envelope relaxation oscillation occur as shown in Fig. 6. The period of the envelope relaxation peaks is about 50 ~ 60 μs, and the width of the initial spike is about 1 μs. After about 600 μs, the envelope of the mode-locked pulses reaches its steady-state value. Similar phenomena have been observed before [34], [35] in the prelase stage of actively mode-locked and Q-switched Nd:YAG lasers, and the envelope relaxation oscillation is the well-known result of the transient interplay among the population inversion, the intracavity photon flux, and the photon decay time [36].

The pulse energy at the peak of the initial spike is increased 40 times over the pulse energy at the steady state when we chop the IR beam inside the cavity while we CW pump the Nd:phosphate glass. The pulse energy increases at the expense of an increase in pulsewidth. Autocorrelation traces of pulses from this mode-locking and relaxation oscillation show the characteristic of a spike on a broader (80~100 ps) shoulder.

Regenerative Amplifier

We have also developed a linear CW-pumped Nd:phosphate glass regenerative amplifier, as shown in Fig. 7. (Like the oscillator, the amplifier is also CW pumped, which allows operation at high repetition rates.) The resonator is constructed from two high-reflection-coated (1.06 μm) plane parallel mirrors and an f = 85 mm focusing lens. This resonator is similar to the oscillator ring resonator except that a different focusing lens and resonator length have been used. A 2 × 15 × 20 mm Nd:phosphate glass slab (Schott LG 760) provides the gain. The cooling scheme for the laser glass slab is

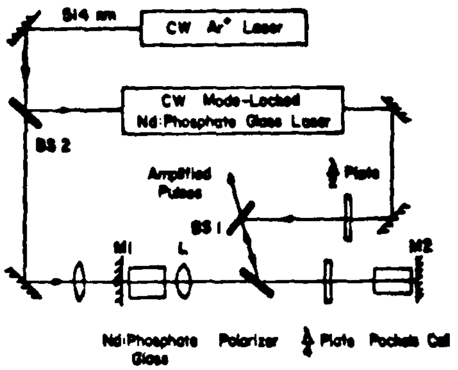

Fig. 7. Schematic of the linear Nd:phosphate glass regenerative amplifier. M1 is a plano mirror with dichroic coatings. M2 is a plano mirror with HR coating. L is a lens with $f = 8.5$ cm. BS1 is a beam splitter with a reflectance of ~10 percent at 1.054 μm. BS2 is a beam splitter with a reflectance of ~50 percent at 514 nm.

the same as that used in the oscillator. A single intracavity Pockels cell [Medox 0690-KDP] is used in the regenerative amplifier. During the on stage, the Pockels cell introduces a quarter-wave retardation, and during the off stage, it introduces a full-wave retardation. The Pockels cell, combined with a quarter-wave plate and a thin film polarizer, traps the injected pulse and later dumps it out of the regenerative amplifier. Phase-locking of the regenerative amplifier with the injected mode-locked pulse is maintained by driving the Pockels cell at 500 Hz downshifted from the 50 MHz driving frequency of the laser oscillator acoustooptic modulator. To minimize loss, all intracavity elements are AR coated at 1.06 μm.

To isolate the regenerative amplifier from the oscillator and extract the amplified pulses from the amplifier, we use an $R = 10$ percent beam splitter. The beam waist of the oscillator is imaged by a lens to match the larger amplifier waist so that the diffraction loss of the injected pulse energy can be minimized. This approach maintains a high energy contrast ratio of the initial injected pulse to the spontaneous emission from the amplifier and thereby minimizes the amplified spontaneous emission.

A portion (~20 pJ) of the 20 ps output pulse train from the CW mode-locked Nd:phosphate glass laser oscillator is injected into the regenerative amplifier. When the regenerative amplifier is pumped with 1.8 W of argon ion laser power, the injected pulse is amplified to maximum energy after about 300 round-trip passes and is then dumped out from the amplifier. An amplified pulse energy of 1 μJ (5×10^4 amplification) has been realized with this regenerative amplifier. (When thermal birefringence is compensated for, then 5 μJ output pulses can be produced. This is discussed later.) The 500 Hz repetition rate is presently limited by the Pockels cell. However, the CW pump scheme should allow a 2 kHz repetition rate operation, ultimately limited by upper-level lifetime.

Preliminary streak camera measurements of the amplified pulsewidth show a primary peak 50 ~ 60 ps in width (Fig. 8) and smaller satellites about 1 ns away. Two causes of this long pulsewidth are possible. One is the gain saturation, which can cause the line narrowing of the gain medium. However, because the line width of Nd:glass is much broader than the pulse bandwidth, this line narrowing will not affect the pulse bandwidth until the amplification is near its peak. Another possible cause could be the SPM, which might occur in the later stage of the amplification process. Although we believe that SPM is not occurring in the oscillator because of the low power density, we should note that the pulse energy can be 40 times greater inside the regenerative amplifier than inside the oscillator. Thus, strong SPM may occur, leading to the pulse broadening observed. Such pulse broadening could be eliminated by compressing the amplifier output with a grating pair. Considering the broad line width of Nd:glass, one could expect amplification of pulses as short as 200 fs. (A low-repetition-rate Nd:glass chirped pulse amplifier and compression system produced 2 ps pulses with the possibility of subpicosecond pulse performance [37], [38].)

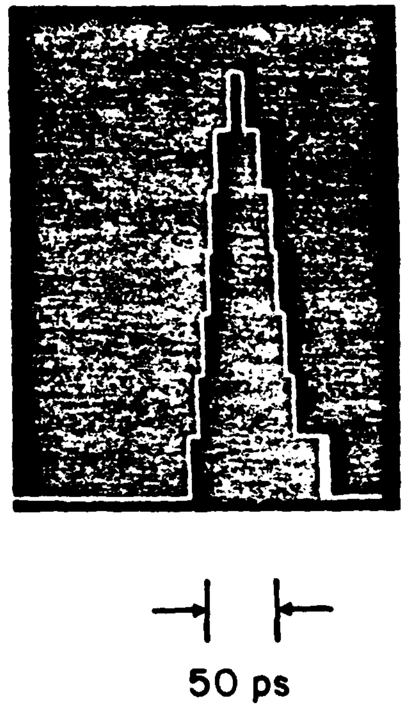

Fig. 8. Streak camera picture of the amplified pulse. The pulsewidth is 50 ps (FWHM).

Even when the regenerative amplifier is aligned to have a net gain greater than one, the relatively long amplification process (~300 roundtrips) indicates that the unsaturated net gain of the regenerative amplifier is small. We find that this small unsaturated net gain is caused by thermal birefringence. Thermal birefringence and thermal lensing effects are well known for high-power Nd:YAG and Nd:glass lasers [39]. Our experimental studies [40], in accordance with theory, show that under tight focusing even a few watts of absorbed heat can cause strong thermal birefringence. Using a mechanical chopper to chop the argon ion laser pump beam, we observe the effect of the thermal birefringence loss. The laser leakage output

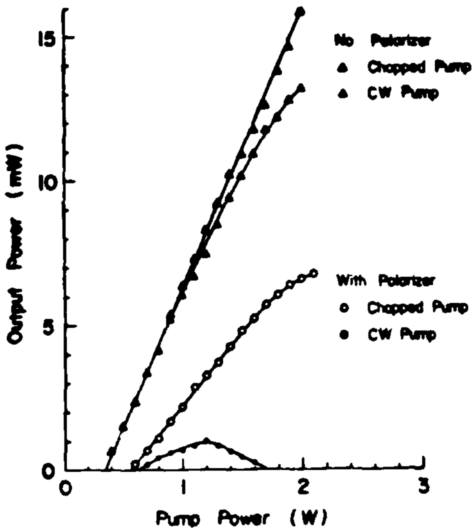

Fig. 9. Laser ouput as observed through mirror M2 of the linear cavity. The Pockels cell and the quarter-wave plate are removed. Outputs for four cases are observed with or without the intracavity polarizer for either chopped or CW pumping. For the chopped pumping case, the plotted power was measured about 600 μs after initial lasing.

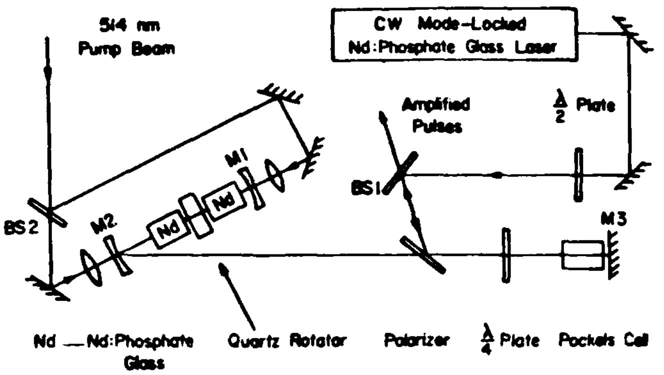

Fig. 10. Schematic of the thermal-birefringence-compensated Nd : phosphate glass regenerative amplifier. The two Nd : phosphate glass slabs are the same (Schott LG 760). M1 is a dichroic-coated plano-concave mirror with R = 10 cm. M2 is a dichroic-coated plano-concave mirror with R = 30 cm. M3 is a plano mirror with HR coating. BS1 is a beam splitter with $R \sim 10$ percent at 1.054 μm and $R \sim 50$ percent at 514 nm.

from one end mirror is monitored by a pin-diode detector, which is calibrated by a caloric power meter. With a polarizer inside the cavity and with the pump beam chopped at a 50 percent duty cycle, the laser output monotonically decreases after the initial relaxation oscillations (about 600 μs) during the lasing period. The laser output about 600 μs after lasing begins is compared to the laser output when CW pumping is used. Similar experiments are done with the polarizer removed. Fig. 9 summarizes our results. Although the laser alignment has not been optimized, the dramatic difference between CW pumping and chopped pumping with and without the intracavity polarizer clearly reflects the effect of the thermal birefringence loss.

There are several possible solutions to the thermal problem. One can use a semiconductor diode laser or diode laser array as the pump source. The diode laser pump at ~ 800 nm has a better quantum efficiency and probably a better branching ratio than the argon ion laser pump at 514 nm. Thus, for a given gain level, the residual heat can be reduced by a factor of more than three as compared to argon-ion laser pumping. Recent experiments with diode-laser-array-pumped solid-state lasers have shown high efficiency [41], [42], and the development of high-power diode-laser-array pumping shows a promising future [43].

To avoid unnecessary heat generation, synchronous pumping up to 2 kHz can replace CW pumping since one does not have to pump longer than the 300 μs fluorescence lifetime of Nd^{3+}. The unnecessary heat generated between each period of energy storage and amplification can thus be removed. High-repetition-rate periodic pumping can be achieved either by using a quasi-CW diode laser array or by simply chopping the pump laser beam at a high repetition rate.

An alternative solution to the thermal problem is a thermal-birefringence-compensated resonator [44]. Fig. 10 is the schematic of a variant. It is designed specifically to accommodate the symmetric double end pumping of two Nd : glass slabs. The 90° crystal quartz polarization rotator, placed between the two Nd : glass slabs, flips the radial and tangential field components at every point in the transverse beam profile. Thus, the difference between the radial index and the tangential index caused by thermal stress in one Nd : glass slab is compensated for in the second Nd : glass slab because the field components have been switched. With this thermal-birefringence-compensated regenerative amplifier, we have amplified the pulse energy to 5 μJ in about 110 round trips at the same 1.8 W pump power used to pump the previously configured regenerative amplifier. (We have end pumped each phosphate glass slab with 0.9 W.) This represents a factor of five increase in the amplified pulse energy and a reduction of about three in the buildup time.

Summary

We have described the performance of a CW actively mode-locked Nd : phosphate glass laser oscillator and a high-repetition-rate Nd : phosphate glass regenerative amplifier. A 100 MHz pulse train at 1.054 μm has been generated with 7 ps pulsewidths and an average output power of >20 mW. By mechanically chopping the Nd : glass laser beam in the cavity, we increased the pulse energy 40 times at the expense of broadening the pulsewidth. Moreover, we found that the gain level of the Nd : phosphate glass laser is important in generating short and coherent laser pulses. At moderate pumping levels, a pulsewidth ~ 20 ps is produced, which agrees with the value expected from a theory for the actively mode-locked homogeneous laser. At high pump levels, even shorter pulses are generated, and phase modulation, introduced through the detuning in the modulation process, is involved in the pulse shaping. By compensating for the thermal birefringence, we designed a regenerative amplifier, which amplified the laser pulses from the CW ac-

tively mode-locked Nd:phosphate glass oscillator to 5 μJ at a 500 Hz repetition rate. In addition, only a single argon-ion laser pumped both the oscillator and the regenerative amplifier. Furthermore, the Nd:glass medium has the potential for amplifying pulses as short as 200 fs at a high repetition rate.

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References

[1] G. R. Fleming and A. E. Siegman, Eds., *Ultrafast Phenomena V*, New York: Springer-Verlag, 1986.
[2] D. H. Auston and K. B. Eisenthal, Eds., *Ultrafast Phenomena IV*, New York: Springer-Verlag, 1984.
[3] M. J. Weber, Ed., *Handbook of Laser Science and Technology, Vol. I, Lasers and Masers*. Cleveland, OH: CRC Press, 1982.
[4] A. A. Kaminskii, *Laser Crystals*, New York: Springer-Verlag, 1981.
[5] A. M. Johnson, R. H. Stolen, and W. M. Simpson, "80 × single stage compression of frequency doubled Nd:yttrium aluminium garnet laser pulses," *Appl. Phys. Lett.*, vol. 44, pp. 729-731, 1984.
[6] J. D. Kafka, B. H. Kolner, T. Baer, and D. M. Bloom, "Compression of pulses from a continuous-wave mode-locked Nd:YAG laser," *Opt. Lett.*, vol. 9, pp. 505-506, 1984.
[7] S. De Silvestri, P. Laporta, and V. Magni, "14-W continuous-wave mode-locked Nd:YAG laser," *Opt. Lett.*, vol. 11, pp. 785-787, 1986.
[8] A. Laubereau and W. Kaiser, "Generation and applications of passively mode-locked picosecond light pulses," *Opt. Electron.*, vol. 6, pp. 1-24, 1974.
[9] H. Al-Obaidi, R. J. Dewhurst, D. Jacoby, G. A. Oldershaw, and S. A. Ramsden, *Opt. Commun.*, vol. 14, pp. 219-222, 1975.
[10] H. Vanherzeele, J. L. Van Eck, and A. E. Siegman, "Colliding pulse mode locking of a Nd:YAG laser with an antiresonant ring structure," *App. Opt.*, vol. 20, pp. 3484-3486, 1981.
[11] J. R. Taylor, W. Sibbett, and A. J. Cormier, "Bandwidth-limited picosecond pulses from a neodymium-phosphate glass oscillator," *Appl. Phys. Lett.*, vol. 31, pp. 184-186, 1977.
[12] T. R. Royt, "Passive mode-locking of the Nd-glass oscillator at high repetition rate with thermally compensated phosphate glasses," *Opt. Commun.*, vol. 35, pp. 271-276, 1980.
[13] C. Kolmeder and W. Zinth, "Theoretical and experimental investigations of a passively mode-locked Nd:glass laser," *Appl. Phys.*, vol. 24, pp. 341-348, 1981.
[14] L. S. Goldberg, P. E. Schoen, M. J. Marrone, "Repetitively pulsed mode-locked Nd:phosphate glass laser oscillator-amplifier system," *Appl. Opt.*, vol. 21, pp. 1474-1477, 1982.
[15] L. S. Goldberg and P. E. Schoen, "Active-passive mode-locking of a Nd:phosphate glass laser using #5 saturable dye," *IEEE J. Quantum Electron.*, vol. QE-20, pp. 628-630, 1984.
[16] T. Tomie, "Picosecond pulse generation by self-phase modulation in an actively mode-locked and Q-switched phosphate glass laser," *Japan. J. Appl. Phys.*, vol. 24, pp. 1008-1017, 1985.
[17] S. Kishida, K. Washio, and S. Yoshikawa, "CW oscillation in a Nd:phosphate glass laser," *Appl. Phys. Lett.*, vol. 34, pp. 273-275, 1979.
[18] S. A. Strobel, P.-T. Ho, C. H. Lee, and G. L. Burdge, "Continuous wave mode-locked neodymium: phosphate glass laser," *Appl. Phys. Lett.*, vol. 45, pp. 1171-1172, 1984.
[19] L. Yan, J. D. Ling, P.-T. Ho, and C. H. Lee, "Picosecond-pulse generation from a continuous-wave neodymium:phosphate glass laser," *Opt. Lett.*, vol. 11, pp. 502-503, 1986.
[20] A. S. L. Gomes, W. Sibbett, and J. R. Taylor, "Compression of Q-switched and mode-locked CW Nd:YAG laser pulses," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 1157-1158, 1985.
[21] B. Zysset, W. Hodel, P. Beaud, and H. P. Weber, "200-femtosecond pulses at 1.06 μm generated with a double-stage pulse compressor," *Opt Lett.*, vol. 11, pp. 156-158, 1986.
[22] I. N. Duling III, T. Norris, T. Sizer II, P. Bado, and G. Mourou, "Kilohertz synchronous amplification of 85-femtosecond optical pulses," *J. Opt. Soc. Amer.*, vol. B2, pp. 616-618, 1985.
[23] The authors are grateful to the Shanghai Institute of Optics and Fine Mechanics for the Nd:phosphate glass slab.
[24] E. P. Ippen and C. V. Shank, "Techniques for measurements," in *Ultrafast Light Pulses: Picosecond Techniques and Applications*, S. L. Shapiro, Ed. New York: Springer-Verlag, 1977, pp. 85-88.
[25] D. W. Hall and M. J. Weber, "Modeling gain saturation in neodymium laser glasses," *IEEE J. Quantum Electron.*, vol. QE-20, pp. 831-834, 1984.
[26] D. J. Kuizenga and A. E. Siegman, "FM and AM mode-locking of the homogeneous laser—Parts I and II," *IEEE J. Quantum Electron.*, vol. QE-6, pp. 694-715, 1970.
[27] A. E. Siegman and D. J. Kuizenga, "Active mode-coupling phenomena in pulsed and continuous lasers," *Opt. Electron.*, vol. 6, pp. 43-66, 1974.
[28] M. B. Morris and T. J. McIlrath, "Portable high-resolution laser monochromator-interferometer with multichannel electronic readout," *Appl. Opt.*, vol.18, pp. 4145-4151, 1979.
[29] R. C. Eckardt, C. H. Lee, and J. N. Bradford, "Temporal and spectral development of mode locking in a ring-cavity Nd:glass laser," *Appl. Phys. Lett.*, vol. 19, pp. 420-423, 1971.
[30] P. Mandel and N. B. Abraham, "Stability analysis of a bidirectional homogeneously broadened ring laser," *Opt. Commun.*, vol. 51, pp. 87-90, 1984.
[31] P. Lett, W. Christian, S. Singh, and L. Mandel, "Macroscopic quantum fluctuations and first-order phase transition in a laser," *Phys. Rev. Lett.*, vol. 47, pp. 1892-1895, 1981.
[32] R. L. Fork, B. I. Greene, and C. V. Shank, "Generation of optical pulses shorter than 0.1 psec by colliding pulse mode locking," *Appl. Phys. Lett.*, vol. 38, pp. 671-672, 1981.
[33] I. V. Tomov, R. Fedosejevs, and M. C. Richardson, "Unidirectional traveling wave operation of a mode-locking Nd:glass ring laser," *Opt. Commun.*, vol. 21, pp. 327-331, 1977.
[34] D. J. Kuizenga, "Short-pulse oscillator development for the Nd:glass laser-fusion systems," *IEEE J. Quantum Electron.*, vol. QE-17, pp. 1694-1708, 1981.
[35] G. F. Albrecht, M. T. Gruneisen, and D. Smith, "An active mode-locked Q-switched oscillator using Nd^{3+} doped glass as the active medium," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 1189-1194, 1985.
[36] A. Yariv, *Quantum Electronics*, 2nd ed. New York: Wiley, 1975, see references therein.
[37] D. Strickland, P. Maime, M. Bowier, S. Williamson, and G. Mourou, "Picosecond pulse amplification using pulse compression techniques," *Ultrafast Phenomena V*, G. R. Fleming and A. E. Siegman, Eds. New York: Springer-Verlag, 1986, pp. 38-42.
[38] P. Maime, D. Strickland, M. Bouvier, and G. Mourou, "Amplification of picosecond pulses to the terawatt level by chirped pulse amplification and compression," in *Dig. Conf. Lasers and Electro-Opt.*, Opt. Soc. Amer., Washington, D.C., 1987, paper FR2.
[39] W. Koechner, *Solid-State Laser Engineering*. New York: Springer-Verlag, 1976, see references therein.
[40] Unpublished.
[41] B. Zhou, T. J. Kane, G. J. Dixon, and R. L. Byer, "Efficient, frequency-stable laser-diode-pumped Nd:YAG laser," *Opt. Lett.*, vol. 10, pp. 62-64, 1985.
[42] W. J. Kozlovsky, T. Y. Fan, and R. L. Byer, "Diode-pumped continuous-wave Nd:glass laser," *Opt. Lett.*, vol. 11, pp. 788-790, 1986.
[43] *Digest of Conference on Lasers and Electro-Optics*. Washington, D.C.: Optical Society of America, 1987.
[44] W. C. Scott and M. de Wit, "Birefringence compensation and TEM_{00} mode enhancement in a Nd:YAG laser," *Appl. Phys. Lett.*, vol. 18, pp. 3, 4, 1971.

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P.-T. Ho, photograph and biography not available at the time of publication.

Chi H. Lee, photograph and biography not available at the time of publication.

G. L. Burdge, photograph and biography not available at the time of publication.

Appendix 2

Generation of High Power, High Repetition Rate, Subpicosecond Pulses by Intracavity Chirped Pulse Regenerative Amplification.

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ABSTRACT

A neodymium phosphate glass regenerative amplifier is used for both pulse energy amplification and spectral broadening. After compression by a grating pair, 0.55 psec pulses of 11 μJ energy are generated at a 370 Hz repetition rate.

Much attention in recent years has been given to pulse compression as a practical technique for generating ultrashort laser pulses.[1-8] Two diverse neodymium laser systems have evolved. One system produces pulses at a high repetition rate (~ 100 MHz) and low pulse energy (< 20nJ).[4-6] The other system generates pulses at a low repetition rate but with high pulse energy (> 1mJ) using chirped pulse amplification and compression.[7,8] In both laser systems, because of the long initial pulse width, a long optical fiber is needed to achieve substantial spectral broadening through self-phase modulation (SPM). The optical fiber has limited power handling capability caused by stimulated Raman scattering or caused by surface melting or both. Although the final pulse energy can be quite high by chirped pulse amplification and compression, the initial pulse energy from the oscillator has to be high enough to generate a substantial spectral broadening. In this letter, we report using a regenerative amplifier for both pulse energy amplification and pulse spectral broadening and chirping through intracavity self-phase modulation.[9,10] With this configuration, we avoid using optical fiber for pulse spectral broadening. The amplified and chirped pulses are then compressed by a grating pair to 0.55 ps with a pulse energy of 11μJ at a 370 Hz repetition rate. Such high energy, subpicosecond pulses at the relatively high rate of 370 Hz fills the gap between the systems at the two extremes.

Figure 1 shows the schematic of the laser oscillator-amplifier system. The output of a single cw argon ion laser at 514nm is split to pump both a cw mode-locked Nd:phosphate glass oscillator and a Nd:phosphate glass regenerative amplifier.[11] The pump beam for the regenerative amplifier is chopped by a mechanical chopper, which is synchronized to the Pockels cell, to reduce the average pump heat loading and thereby minimize the thermal birefringent loss.[11] The total pump power used is 3.6 watts. The oscillator is actively mode-locked by an acousto-optic modulator. Using an intracavity etalon for bandwidth selection, we can generate Fourier-transform-limited pulses of about 11 ps at 100 MHz repetition rate with a 50 mW average power. A seed pulse (~5 pJ) from the oscillator is injected into the regenerative amplifier. After about 60 round trips in the regenerative amplifier, the pulse is amplified to about 27 μJ before it is switched out. With eighty percent transmission of the beam splitter, about 21 μJ pulse energy is coupled out. The regenerative amplifier is operated at a 370 Hz repetition rate.

Because of the short input pulse width, high amplified pulse intensity and multiple passes, a strong self-phase modulation occurs in the Nd:phosphate glass inside the regenerative amplifier. We observed the amplified pulse bandwidth broadening from 2.0 Å to about 15 Å while the pulse width broadened slightly to 12 ps. These amplified and chirped pulses are then sent through a grating pair. The 1800 lines/mm grooved gratings are placed at an incident angle of about 80°. Emerging from the grating compressor, the pulse (assumed to be Gaussian) is compressed to a width of 1.25 ps. The pulse duration-bandwidth product of 0.5 is nearly Fourier-transform-limited.

The intracavity SPM can be further enhanced by inserting a nonlinear material inside the regenerative amplifier. We have placed a second, unpumped slab of Nd:phosphate glass next to the pumped Nd glass slab. This enhances the intracavity SPM and the pulse bandwidth is broadened further to about 34 Å (Figure 2). Subsequently, the pulse is compressed to 0.55 ps (Figure 3) by the same grating pair. Again, a Gaussian pulse shape is assumed and the pulse width-bandwidth product is 0.5. The pulse energy after compression is 11μJ and the pulse repetition rate is 370 Hz.

An estimate of the spectral broadening due to multipass SPM confirms the observed broadened pulse spectral width. Assuming a negligible group velocity dispersion, we approximate the spectrum broadening due to SPM by:

$$\Delta\lambda_{SPM} = \frac{4\lambda \ell \gamma \Sigma I_k}{c\ \tau_p} = \frac{4\lambda \ell \gamma K_{eff} I_p}{c\ \tau_p}$$

where γ and ℓ are the nonlinear index of refraction and the length of the neodymium glass respectively, I_k is the pulse intensity at the kth round trip and I_p is the peak amplified pulse intensity, and K_{eff} is an effective round trip number which gives $\Sigma I_k = K_{eff} I_p$. With $\ell = 4$ cm (two slabs), $\gamma = 3 \times 10^{-16}$ cm^2/W, [12] $\tau_p = 11$ ps, $I_p \approx 2.3 \times 10^{10}$ W/cm^2, and $K_{eff} = 9$, we obtain $\Delta\lambda_{SPM} = 32$ Å which is in good agreement with the observed broadened spectral width.

Our method of intracavity-chirped pulse amplification and compression by using a regenerative amplifier is essentially independent of the initially very weak pulse energy since a strong SPM can always occur in the later part of the regenerative amplification. With a seed pulse of definite temporal and spectral characteristics from a stable oscillator, the chirped pulse spectral broadening and the compressed pulse width are reproducible. In addition, this approach offers much higher power handling capability than conventional pulse compression using an optical fiber. It essentially uses the regenerative amplifier as a large scale optical waveguide for producing substantial SPM. The technique can be applied to other types of laser systems, and various nonlinear materials may be used to enhance the SPM.

In conclusion, we have generated subpicosecond pulses with high pulse energy at a relatively high repetition rate. By enhancing the intracavity self-phase modulation in a Nd:phosphate glass regenerative amplifier, we can both amplify the picosecond pulse and broaden the pulse spectrum. The spectrally broadened pulses are then compressed to 0.55 ps with a pulse energy of 11 μJ at a 370 Hz repetition rate. By not using an optical fiber for pulse compression, we can generate high power pulses.

The authors would like to thank Dr. J. Goldhar for helpful discussions. This work was supported in part by the Air Force Office of Scientific Research.

REFERENCES

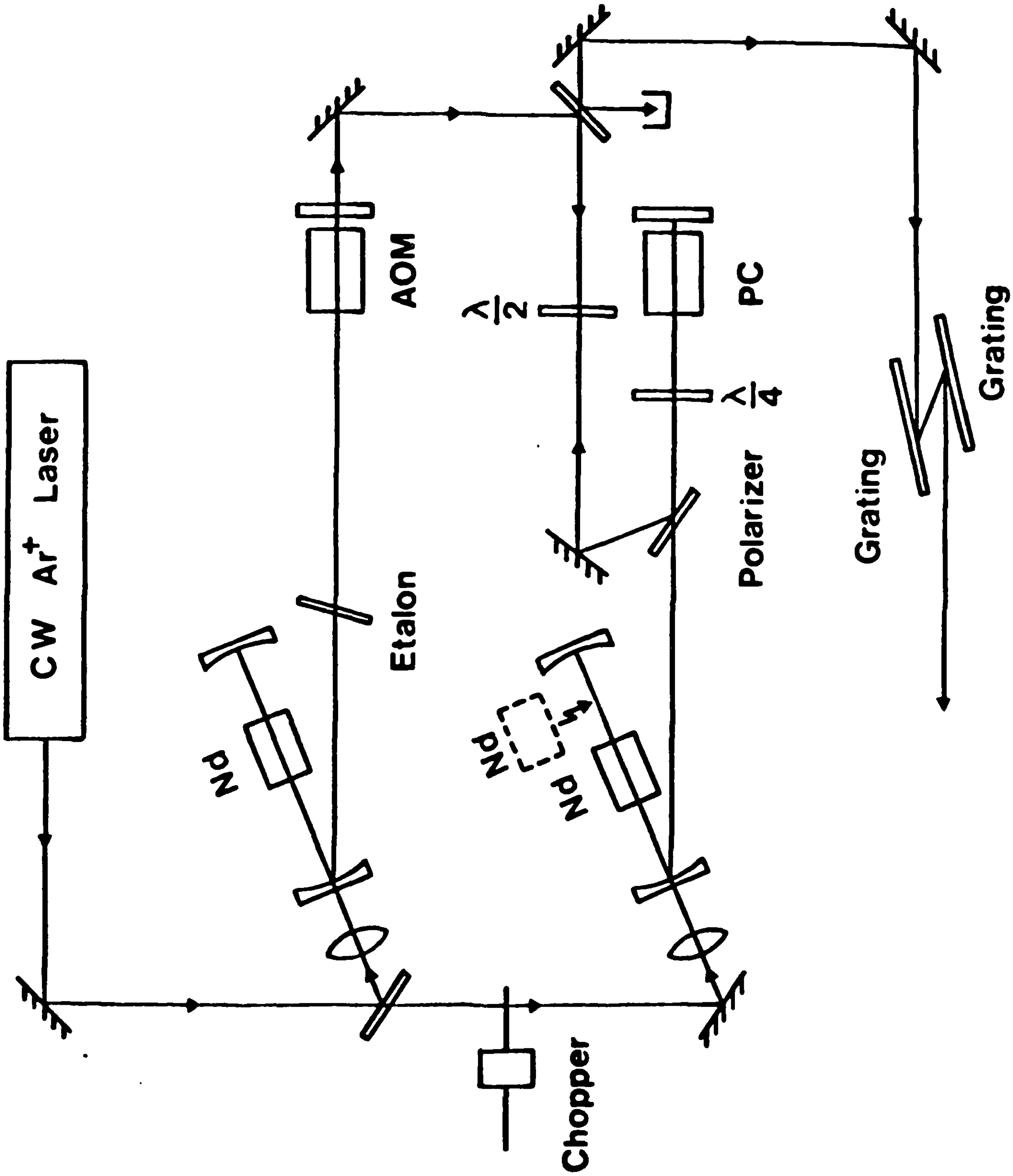
1. J.G. Fujimoto, A.M. Weiner, and E.P. Ippen, *Appl. Phys. Lett.* 44, 832 (1984).
2. J.M. Halbout and D. Grischkowsky, *Appl. Phys. Lett.* 45, 1281 (1984).
3. W.H. Knox, R.L. Fork, M.C. Downer, R.H. Stolen, C.V. Shank, and J.A. Valdmanis, *Appl. Phys. Lett.* 46, 1120 (1985).
4. A.M. Johnson, R.H. Stolen, and W.M. Simpson, *Appl. Phys. Lett.* 44, 729 (1984).
5. J.D. Kafka, B.H. Kolner, T.Baer, and D.M. Bloom, *Opt. Lett.* 9, 505 (1984).
6. B. Zysset, W. Hodel, P. Beaud, and H.P. Weber, *Opt. Lett.* 11, 156 (1986).
7. D. Strickland, P. Maine, M. Bouvier, S. Williamson, and G. Mourou, in *"Ultrafast Phenomena V"*, G.R. Fleming and A.E. Siegman, Eds,. Springer-Verlag, Berlin p. 38 (1986).
8. P. Maine, D. Strickland, P. Bado, M. Pessot, and G. Mourou, *IEEE J. Quantum Electron.*, Vol. QE-24, 398 (1988).
9. R.C. Eckardt, Chi H. Lee, and J.N. Bradford, *Appl. Phys, Lett.* 19, 420 (1971), and R.C. Eckardt, Chi H. Lee, and J.N. Bradford, *Optoelectronics* 6, 67 (1974).
10. J. Van Laak, J.F. Giuliani, and Chi H. Lee, *Phys. Rev. A*, 22, 2122 (1980).
11. L. Yan, J.D. Ling, P.-T. Ho, C.H. Lee, and G.L. Burdge, IEEE *J. Quantum Electron.*, QE-24, 418 (1988).
12. D.C. Brown, "High Peak Power Nd:Glass Laser Systems", Springer-Verlag, Berlin, (1981).

FIGURE CAPTIONS

Figure 1. Schematic of the Nd:phosphate glass oscillator and regenerative amplifier. Nd - Nd:phosphate glass. AOM - acousto-optic modulator. PC - Pockels cell. In the first part of the experiment, only one Nd:phosphate glass slab as a gain medium was used in the regenerative amplifier. In the second part of the experiment, a second unpumped Nd:phosphate glass slab was added to the regenerative amplifier to enhance the self-phase modulation.

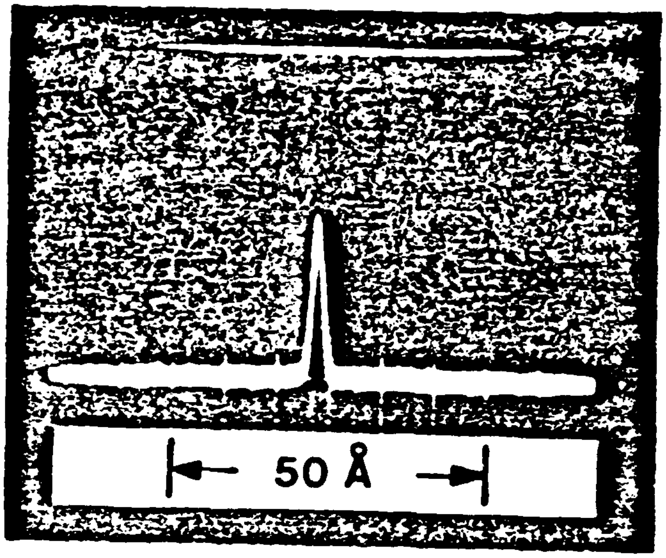
Figure 2. Pulse spectra. (a) Spectrum of pulse from oscillator. (b) Spectrum of amplified pulse from regenerative amplifier.

Figure 3. Autocorrelation trace of compressed pulses.

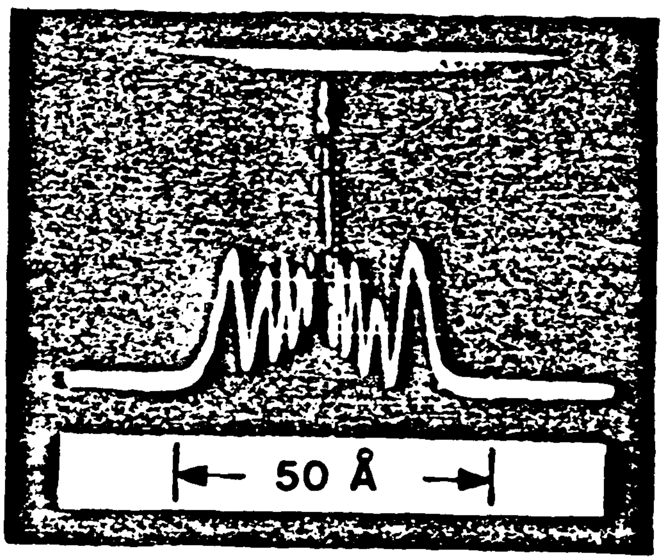


CW Ar+ Laser
AOM
Etalon
Nd
Nd
Nd
$\frac{\lambda}{2}$
$\frac{\lambda}{4}$
PC
Polarizer
Grating
Grating
Chopper

Figure 1



(a)



(b)

Figure 2

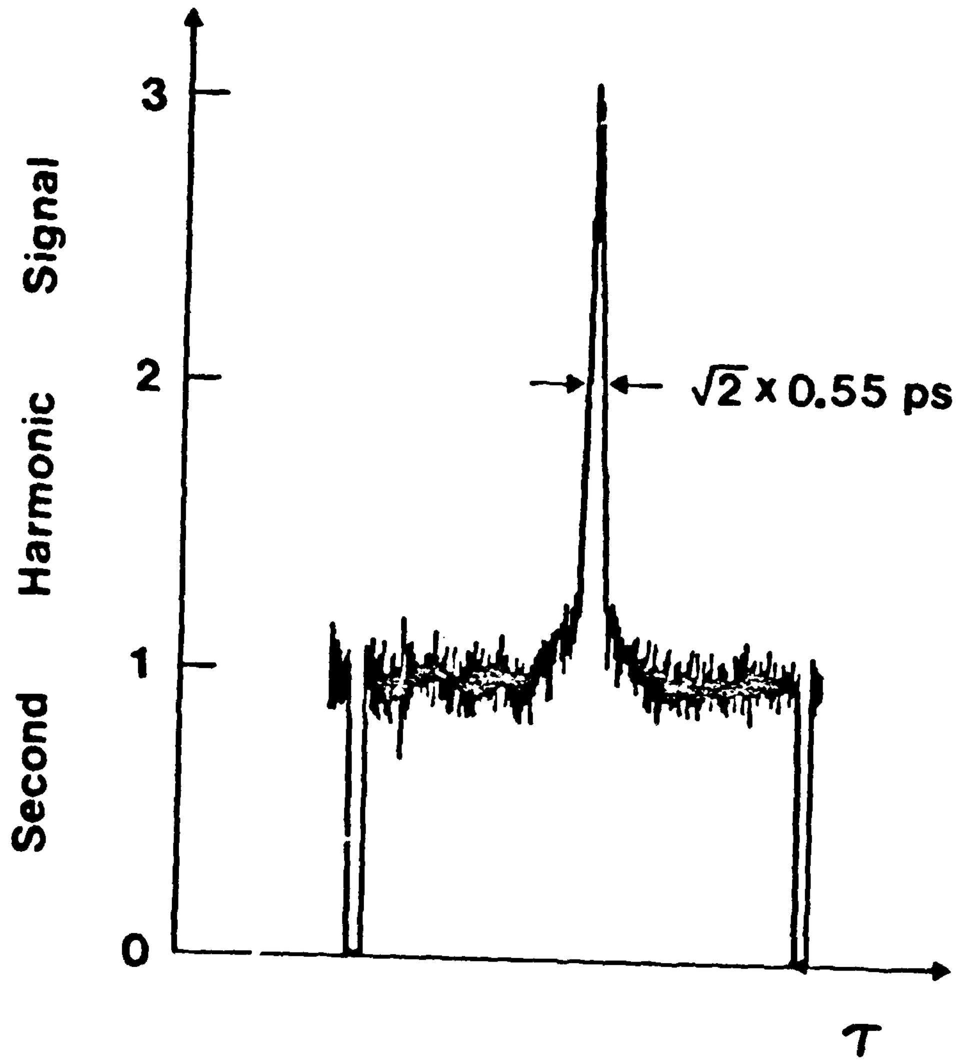


Figure 3

Appendix 3

Femtosecond Pulse Generation at 1.05μm Using Self-Phase Modulation in a Regenerative Amplifier and a Fiber.

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ABSTRACT

Pulses of 30 fs duration at 1.054 μm are generated by pulse compression in two stages, using self-phase modulation in a Nd:phosphate glass regenerative amplifier and an optical fiber.

Femtosecond Pulse Generation at 1.05μm Using Self-Phase Modulation in a Regenerative Amplifier and a Fiber.

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To date most ultrashort optical pulses have been generated in the visible spectrum.[1-3] The pulse widths in the near infrared from neodymium laser systems at 1.06μm are much longer. Even after two stages of pulse compression, the shortest pulse width generated at 1.06μm is still only 200 fsec.[4] The problem with previous short-pulse laser systems operating at 1.06μm is that the pulse energy is limited by the stimulated Raman scattering in the optical fiber to about 20nJ.[5] This low pulse energy is not high enough to generate sufficient self-phase modulation to compress a pulse shorter than 200 fsec.[4] In this paper we report much shorter pulse generation by using a regenerative amplifier both to amplify the pulse energy and to broaden the pulse spectrum by intracavity self-phase modulation for the first stage of pulse compression. The addition of an optical fiber further compresses the to 30 fsec at 1.054μm. To our knowledge, these are the shortest pulses produced at this wavelength.

Figure 1 shows the schematic of the laser system. A cw argon-ion laser pumps both the Nd:phosphate glass cw oscillator and the high-repetition-rate regenerative amplifier. The oscillator, which is actively modelocked by an acousto optic modulator, generates stable pulses of ~11 psec at 100MHz with an average power of 50mW. An injection pulse (~5pJ) is coupled into the regenerative amplifier, which not only amplifies the pulse energy to ~27μJ but also broadens the pulse bandwidth to ~34 Å by intracavity self-phase modulation. Subsequently, these amplified, spectrally-broadened and chirped pulses are compressed by a pair of gratings (1800 grooves/mm) to 0.55 psec with a pulse energy of 11μJ. The amplifier operates at a 370 Hz repetition rate.

After the first compression, the subpicosecond pulses are coupled into an optical fiber. (The pulse energy exiting the amplifier must be attenuated to avoid fiber end surface damage and to limit the broadened pulse bandwidth for optimum compression.) The fiber broadens the pulse bandwidth to 500 Å. Pulses are then compressed further by a second pair of gratings (600 grooves/mm). Figure 2 shows the autocorrelation of the compressed pulses with a 30 fsec pulse width for a $sech^2$ pulse shape. A reasonable ~ 70nJ pulse energy was obtained.

In summary, we have used the intracavity self-phase modulation in a Nd:glass regenerative amplifier as the first stage of compression to generate 0.55 ps, 10μJ pulses at a 370 Hz repetition rate. Then using an optical fiber as the second stage, we further compressed the pulses to 30 fs.

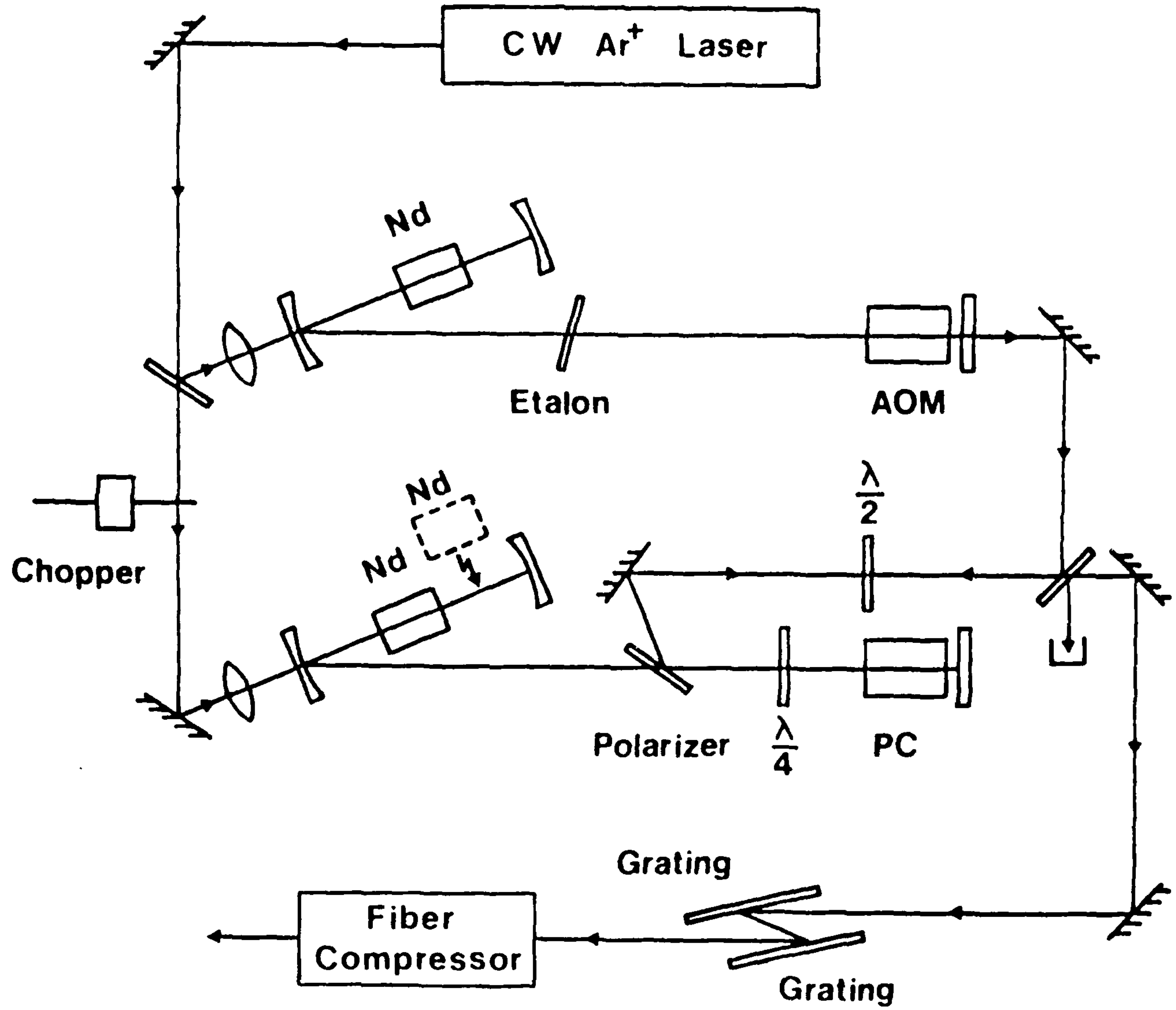
REFERENCES

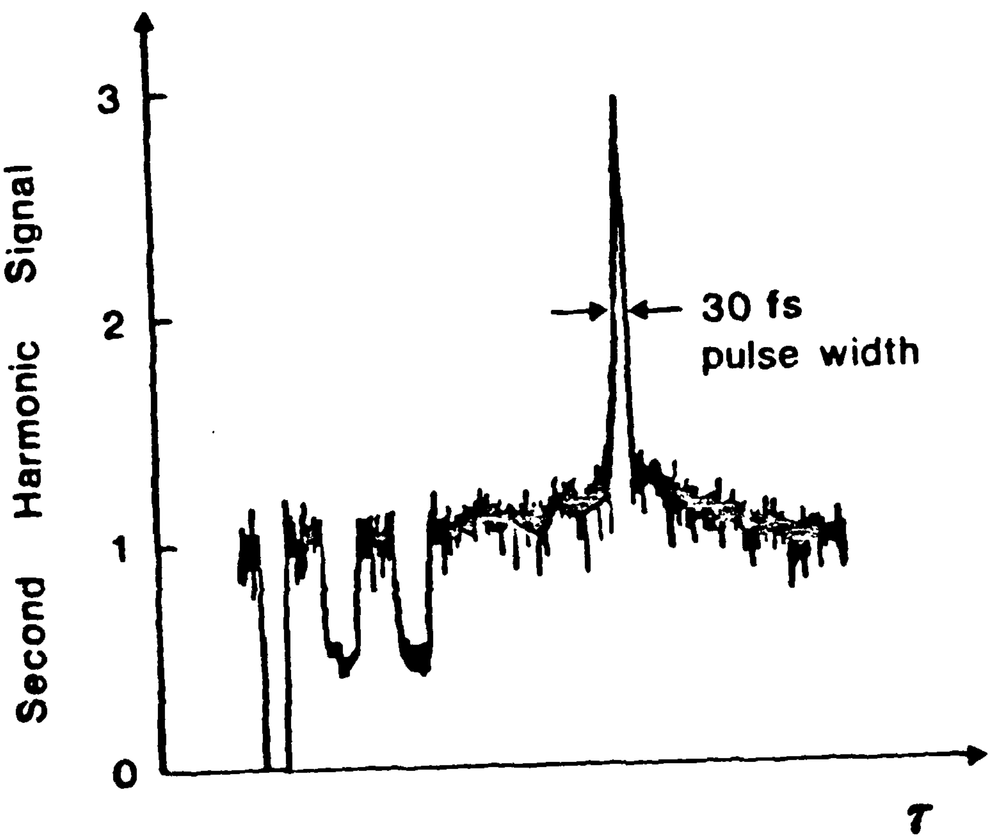
1. J.G. Fujimoto, A.M. Weiner, and E.P. Ippen, *Appl. Phys. Lett.* 44, 832 (1984).
2. J.M. Halbout and D. Grischkowsky, *Appl. Phys. Lett.* 45, 1281 (1984).
3. W.H. Knox, R.L. Fork, M.C. Downer, R.H. Stolen, C.V. Shank, and J.A. Valdmanis, *Appl. Phys. Lett.* 46, 1120 (1985).
4. B. Zysset, W. Hodel, P. Beaud, and H.P. Weber, *Opt. Lett.* 11, 156 (1986).
5. J.D. Kafka, B.H. Kolner, T. Baer, and D.M. Bloom, *Opt. Lett.* 9, 505 (1984).

FIGURE CAPTIONS

Figure 1. Schematic of the Nd:phosphate glass oscillator and regenerative amplifier. Nd - Nd:phosphate glass. AOM - acousto-optic modulator. PC - Pockels cell. The second unpumped Nd:phosphate glass slab is added to the regenerative amplifier to enhance self-phase modulation.

Figure 2. Autocorrelation trace of compressed pulses after the second stage pulse compressor. A $sech^2$ pulse shape is assumed.


CW Ar+ Laser
Nd
Etalon
AOM
Chopper
Nd
Nd
λ/2
Polarizer
λ/4
PC
Grating
Fiber Compressor
Grating



$\mathcal{E}_p \simeq 70\ nJ$.

Appendix 4

TUM50 Photoconductive switching in diamond under high bias

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Because of its unique electrical and thermal properties, diamond is a very interesting material for photoconductive switching. Previous studies[1,2] showed that it is capable of fast response and high switching efficiency when irradiated with UV laser pulses. The third harmonic of a Nd laser at 355 nm and a KrCl laser at 206 nm were used for switching. We report the observation of the nonlinear dependence of mobility and carrier lifetime on high bias fields (up to 1 MV/cm); a KrF laser at 248.6 nm and a N_2 laser at 337 nm were used.

Since the laser power required for switching a photoconductor is a strong function of the interelectrode gap, to take advantage of the high insulating strength of diamond, we constructed a photoconductive switch with a high aspect ratio (Fig. 1). The diamond was a natural type II crystal, and eutectically contacted metal electrodes were fabricated by the manufacturer (Dubble Dee Diamond).

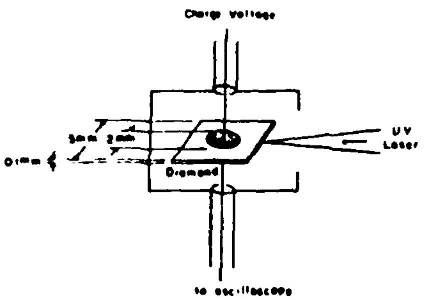
A low-power KrF laser output (3 mJ/20 ns) focused on the switch resulted in good switching efficiency ($\eta \geq 90\%$) for all bias voltages up to 10 kV. A direct current charge was used up to 6 kV with a switch container filled with 1 atm of SF_6. For higher voltages, the container was filled with distilled water, and the pulse bias was used up to 10 kV. This allowed us to study the switching in diamond with applied fields up to 1 MV/cm, which is much higher than applied in previous work.[1,2] With maximum laser power, the switch resistance was much less than the 50-Ω impedance of the transmission lines, and it is, therefore, hard to calculate it from the output pulses. Measurements of resistance at lower irradiating intensities showed that the conductivity at low bias voltages was substantially higher than that at high bias, as shown in Fig. 2.

Very similar behavior was observed at 248 and 337 nm, and even switching efficiencies were approximately the same for the same input powers. The 337-nm laser pulse was ~1 ns, and the observed electrical pulse at low bias was ~15% wider, implying that the carrier lifetime was ~0.5 ns. When the bias voltage was increased to ~1 kV, the electrical and laser pulse shapes coincided, showing a decrease in the response time of the switch.

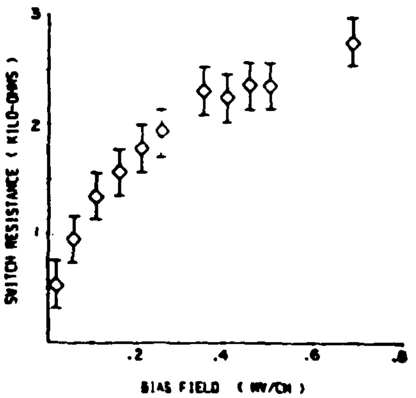
Further investigation of response time of the switch and of physical processes occurring under high bias conditions is in progress.

(Poster paper)

1. P. T. Ho, C. H. Lee, J. C. Stephenson, and R. R. Caranagh, Opt. Commun. 46, 202 (1983).
2. H. M. van Driel, R. F. Code, D. T. Moss, and P. K. Bharadual, Proc. Soc. Photo-Opt. Instrum. Eng. 439, 101 (1983).



TUM50 Fig. 1. Photoconductive diamond switch.



TUM50 Fig. 2. Resistance as a function of bias field for a switch irradiated with peak intensity of 10^8 W/cm^2 at 249 nm.

Evolution of gain and absorption in a CW modelocked dye laser

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Abstract

We have measured the evolution of the gain (rhodamine) and absorber (DODCI) dyes inside a CW modelocked dye laser. The recovery time of either dye after the passage of the intra-cavity pulse was found to be much longer than 1 picosecond. However, a probe pulse passing through one dye after the other experienced a net gain which lasted only about 1 picosecond, the duration of the pulse. The results are consistent with the mechanism of pulse formation in a dye laser modelocked by a slow saturable absorber proposed by New and Haus.

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Evolution of gain and absorption in a CW modelocked dye laser

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The CW dye laser using rhodamine as the gain medium and DODCI as the saturable absorber was first modelocked in 1972 to generate picosecond pulses [1]. The first experiment using these picosecond pulses was to measure the recovery time of the absorber DODCI. The measured recovery time, about 1 ns and 1,000 times longer than the pulses generated [2], caused some surprise. Since according to the prevailing theories at that time, the recovery time of saturable absorber used in modelocking should be shorter than the width of pulses generated. New [3] and Haus [4] proposed a solution — the dynamics of gain saturation must be taken into account. Haus obtained a closed-form solution to the pulse shape, hyperbolic-secant. The hyperbolic-secant pulse shape was verified [5], but there has been no more experimental work on the fundamental pulse forming mechanism. Instead, most work has been done in the important task of further pulse shortening using techniques like "colliding pulses" [6], or removing pulse limitations in optical elements by compensating group velocity dispersion with prisms [7]. As a result of these advances, pulses in the femtosecond region can be generated directly from a dye laser. And the dye laser still remains the only system which can generate short pulses with this method. To develop other lasers, some more work should be done to confirm the basic pulse forming mechanism. For example, in semiconductor laser materials, the key parameters in New's and Haus' theories, relaxation time and cross-section, are roughly the same as those of the dyes. In this letter, we report results on probing the saturable gain and the saturable absorber in a dye laser when it is operating modelocked.

The experimental set-up is shown in Fig 1. It contains a colliding-pulse modelocked dye laser [6]. The laser ring has three plane mirrors. A pair of concave mirrors (radius = 10 cm) are used to focus the beam on the gain jet (rhodamine 590); a pair of lenses (focal length = 2.2 cm), on the saturable absorber jet (DODCI). The solvents for both dyes are ethylene glycol. The concentration of rhodamine is $2.5 \times 10^{-3}M$. The absorber concentration, $10^{-4}M$, is lower than usual as the jet is thicker; the jet nozzle has not been squeezed as commonly done. Both jet nozzles have 0.5 mm openings. The lasing wavelength is 0.62 μm. Typically, the dye laser emits about 10 mW average power at 4.5 watts of argon pump power. The pulse round trip time is 10 ns. No attempt was made to minimize the pulsewidth, which is between 0.5 ps to 1 ps, depending on the operating condition. The main reason for the relatively long pulsewidths is the pair of lenses used to focus the counter-propagating beams on the saturable absorber. The choice of lenses will be explained below. An output pulse train, after a delay of about one cavity round trip time, was redirected back to the laser to measure three events: (1) the time evolution of the absorber; (2) the time evolution of the gain; and (3) the time evolution of the combined gain and absorber. (For the sake of clarity, only the probing of the absorber is shown in Fig. 1.) The measurements were taken by the standard pump-probe technique, with the strong pulses circulating inside the laser resonator as the pump and the output pulse train as the probe. The intracavity beam power is estimated to be one watt; the probe beam, under 1 mW. The time-averaged transmission of the probe as a function of delay relative to the pump measures the evolution of the medium under probe [8].

Spatial overlap of the pump and probe pulses was difficult to achieve in this experiment, since the intracavity beams were tightly focused on the dye jets. Initially, a pair of mirrors were used to focus the beams on the absorber. The astigmatism introduced in the probe beam proved excessive, so a pair of lenses were used instead, with the result that the pulse width was broadened from 0.1-0.3 ps to 0.5-1.0 ps. An additional difficulty arised in measuring the combined transmission through the absorber and the gain. The probe beam and the pump beam have to be spatially separated, yet the difference in optical path length they travel between the absorber and the gain must be well within the pulse width. After careful alignment, we estimated that the path length difference was no more than 0.2 ps. Had we operated the laser in the femtosecond region, the combined transmission measurement would have been impossible.

Results from the experiment are shown in Fig. 2. Fig. 2a and Fig. 2b show, respectively, the transmission through the saturable absorber (DODCI) alone, and through the gain (rhodamine 590) alone. (The sharp corners in Fig. 2 are the "coherence artifacts" described in Ref. 8.) It can be seen that during the passage of the strong intracavity pulse, both the gain and the absorber were saturated, but neither recovered immediately afterwards. When the probe pulse passed through the absorber and then through the gain, the transmission was entirely different (Fig. 2c) – the net gain (gain less absorption) shows a peak on the order of the pulse width (1 ps). Thus the combined saturable gain and saturable absorption can indeed provide a net gain which lasts only about as long as the pulses, even though either alone cannot.

In conclusion, our results are consistent with the pulse forming mechanism proposed by New [3] and Haus [4], and that absorptive effects alone in slow media (as opposed to dispersive) are sufficient to produce pulse modulation on a time scale several orders shorter than system response times.

Acknowledgements

This work was supported in part by the Air Force Office of Scientific Research. The authors are grateful to Dr. C.V. Shank and Dr. E.P. Ippen, for their information on the dye laser. Y.-H. Shih and T. N. Ding provided technical assistance, and L. Vittoria made some preliminary measurements.

Figure Captions

Figure 1. Experimental Set-Up.

Figure 2.

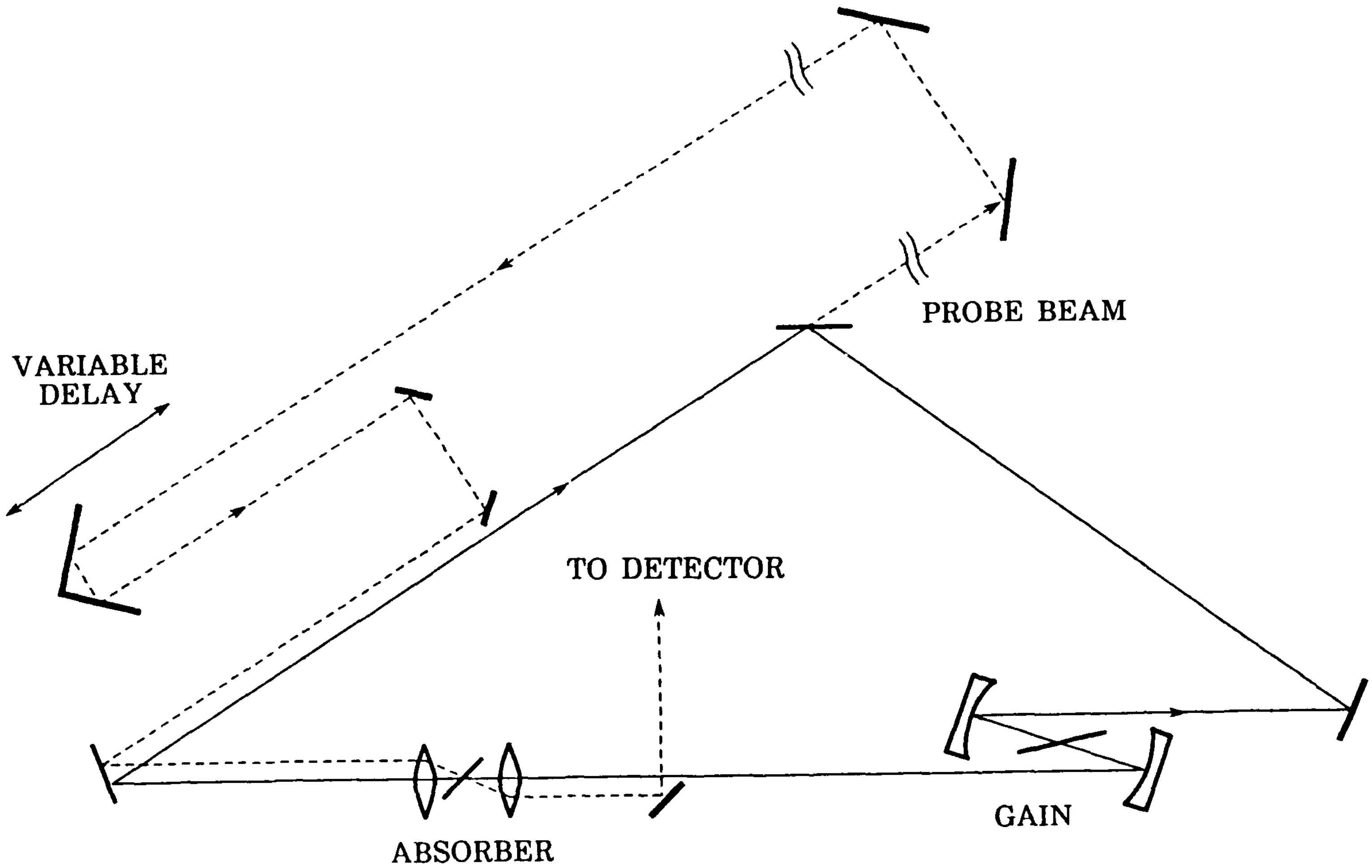
(a) Transmission through the absorber dye (DODCI) alone.

(b) Transmission through the gain dye (rhodamine 590) alone.

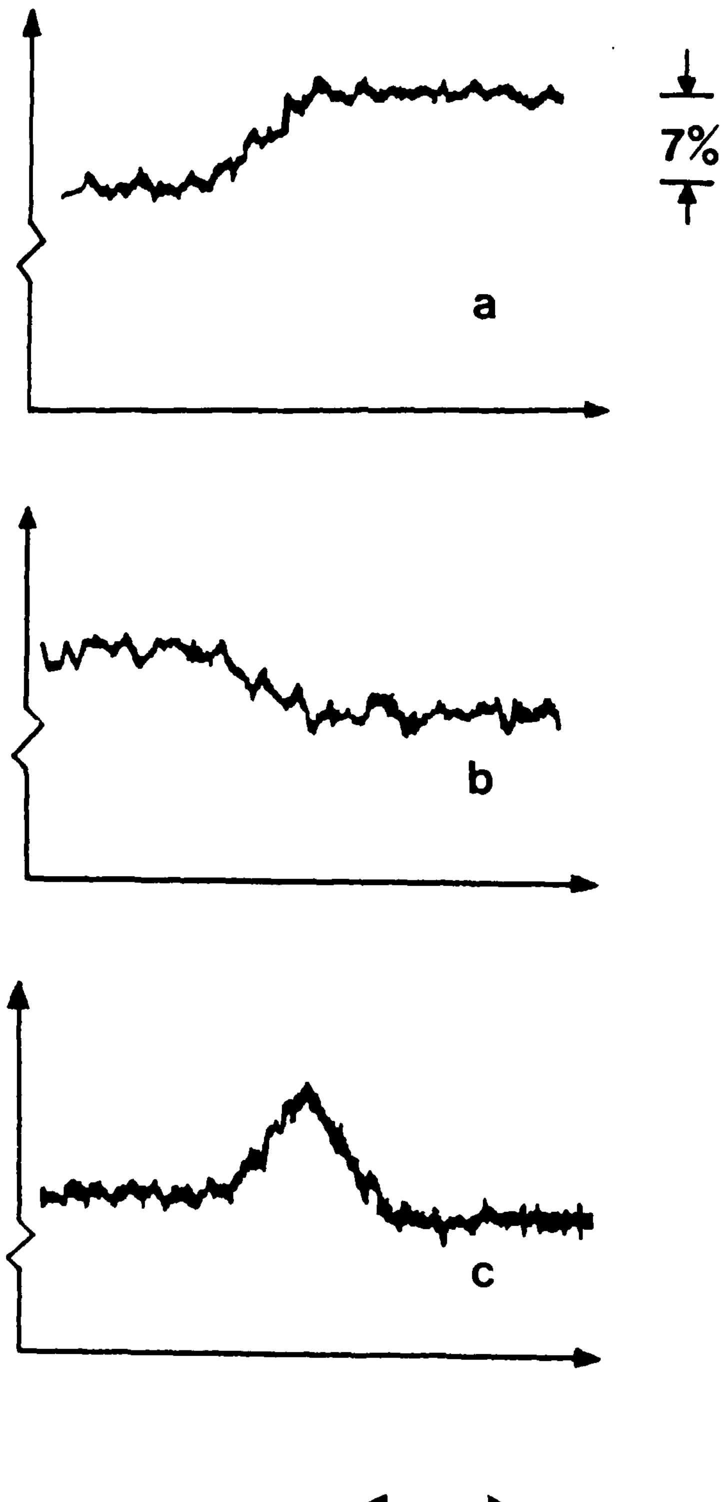
(c) Transmission through the absorber dye and then through the gain dye.

References

1. E.P. Ippen, C.V. Shank, A. Dienes, Appl. Phys. Lett., *21*, 348 (1972).
2. C.V. Shank and E.P. Ippen, "Modelocking of Dye Lasers" in *Dye Lasers*, ed. F.P. Schäfer, Springer-Verlag, N.Y., 1977.
3. G.H.C. New, IEEE J. Quan. Elec., *QE-10*, 115 (1974).
4. H.A. Haus, *ibid.*, *QE-11*, 736 (1975).
5. I.S. Ruddock and D.J. Bradley, Appl. Phys. Lett., *29*, 296 (1976).
6. R.L. Fork, B.I. Greene, and C.V. Shank, Appl. Phys. Lett., *38*, 671 (1981).
7. J.A. Valdmanis, R.L. Fork, and J.P. Gordon, Opt. Lett., *10*, 3 (1985).
8. E.P. Ippen and C.V. Shank, "Techniques for Measurement" in *Ultrashort Light Pulses*, ed. S.L. Shapiro, Springer-Verlag, N.Y., 1977.



PROBE BEAM
VARIABLE
DELAY
TO DETECTOR
ABSORBER
GAIN


7%
a
b
c
1 ps